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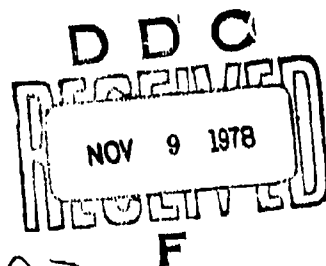
SUFFIELD TECHNICAL PAPER

NO. 486

THE IMPACTION FORCE OF AIRBORNE PARTICLES
ON SPHERES AND CYLINDERS (U)

by

Stanley B. Mellisen



Project No. 20-90-03

September 1978



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14 DRES-TP-1186

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ABSTRACT

The effect of dust on aerodynamic drag of spheres and cylinders was calculated by using a mathematical model developed for this purpose. The results were compared to experiments previously done by other workers. The calculated and experimental results agree favourably, showing that the mathematical model is satisfactory. Impaction efficiencies and drag coefficients due to dust alone were then obtained using the model for a wide range of the inertia parameter and the results are presented graphically. The model can also be used for calculating velocity distributions and points of impact for a stream of airborne particles flowing over a sphere or cylinder.

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NOTATION

A	frontal area of target, cm^2
A_d	far upstream cross sectional area of the envelope of particles which eventually hit the sphere or cylinder, cm^2
a	tube radius, cm
C_D	dimensionless drag coefficient for spheres or cylinders in air
C_{DC} or C_{DS}	drag coefficient of cylinder or sphere due to stream of particles alone
C_{De}	total effective drag coefficient for spheres or cylinders due to particles and air together
C_{DL}	drag coefficient for spheres in tubes adjusted to a sphere in free space by the Landenburg correction
C_{DpU}	drag coefficient for particles alone adjusted from v_{rms} to U
d	particle diameter, cm
E_m	impaction efficiency of particles on a target
F	force exerted on a target by the air and total stream of particles hitting it, dynes
F_a	force exerted on a target by the air alone, dynes
F_s or F_c	force exerted on the sphere or cylinder by the total stream of particles which hit it, dynes
F_p	force exerted on a target by the particles alone travelling in air, dynes
L	cylinder or sphere radius, cm
m'	total mass of particles which had its momentum changed in unit time, g s^{-1}
p_s or p_c	drag pressure on sphere or cylinder due to stream of particles alone, dynes cm^{-2}
r	distance from any point to the origin, cm
t	time, seconds
U	free-stream velocity, cm s^{-1}
u	local fluid velocity, cm s^{-1}

u_r	radial component of fluid velocity, cm s^{-1}
u_θ	circumferential component of fluid velocity, cm s^{-1}
v	local particle velocity, cm s^{-1}
v_{rms}	root-mean-square free stream particle speed upstream near target position, cm s^{-1}
v_x	component of particle velocity parallel to free field flow direction immediately before impact, cm s^{-1}
v_x'	component of particle velocity parallel to flow direction immediately after impact and reflection, cm s^{-1}
v_{x0}	far upstream particle velocity, cm s^{-1}
v_y	component of particle velocity perpendicular to free field flow direction immediately before impact, cm s^{-1}
Δv_x	change in the component of particle velocity parallel to the free stream flow direction caused by reflection from the sphere or cylinder, cm s^{-1}
x	co-ordinate (origin at centre of sphere or cylinder) of particle position parallel to free stream flow direction, cm
y	transverse co-ordinate of particle position, cm
y'	off-axis distance of a particle at point of impact with the sphere or cylinder, cm
y_c	far upstream transverse co-ordinate of the envelope of particles which eventually hit the sphere or cylinder, cm
α	angle of incidence of a particle against the sphere or cylinder, radians
β	angle between particle direction and free field flow direction just before the particle hits the sphere or cylinder, radians
γ	total angle change of a particle from its far upstream direction to its direction after reflection from the cylinder or sphere, radians
θ	polar angle between x axis and <u>radius vector</u> to particle position, radians
μ	absolute velocity of fluid, poise
ρ	fluid density, g cm^{-3}
ρ^*	total mass of particles and air per unit volume of space, g cm^{-3}
ρ_p	uniform particle density per unit volume of air far upstream, g cm^{-3}

σ particle density, g cm^{-3}

The following were dimensionless:

$f(\bar{y})$	change in component of particle velocity due to reflection from sphere or cylinder as a function of off-axis distance far upstream
K	particle inertia parameter
Re	spherical particle Reynolds number in flow influenced by presence of sphere or cylinder
Re_0	spherical particle Reynolds number in free stream
\bar{r}	$\frac{r}{L}$, distance from any point to the origin
T	time $\frac{tU}{L}$
\bar{u}	local fluid velocity $\frac{u}{U}$, \bar{u}_x and \bar{u}_y are x and y components
\bar{v}	local particle velocity $\frac{v}{U}$, \bar{v}_x and \bar{v}_y are x and y components
\bar{v}_x	$\frac{d\bar{x}}{dT}$, parallel component of particle velocity
\bar{v}_y	$\frac{d\bar{y}}{dT}$, transverse component of particle velocity
\bar{x}	parallel co-ordinate $\frac{x}{L}$
\bar{y}	transverse co-ordinate $\frac{y}{L}$
\bar{y}_d	far upstream transverse co-ordinate of the envelope of particles which eventually hit the cylinder
\bar{y}_i	co-ordinate of particle used in discretization for integration; y_i increases with i from $\bar{y}_1 = 0$ to $\bar{y}_n = \bar{y}_d$
ϕ	dimensionless group independent of drop size formed by combining Re_0 and K

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1. INTRODUCTION

Extensive studies have been made of the drag exerted on spheres and transverse cylinders by moving air (Schlichting, 1960) and attempts have been made to determine the effect of introducing dust into the air stream (Gillespie and Gunter, 1957; 1959). Also, the trajectories of water drops moving in the neighborhood of a circular cylinder placed in a uniform stream of air have been calculated by numerical solution of the equations of motion (Glauert, 1940) and with a mechanical analog (Brun et al., 1953). The latter method has been used in conjunction with flight instruments used to study droplet size and distribution in icing clouds (Brun and Mergler, 1953). Measurements of aerodynamic drag on circular cylinders due to the blast wave from large TNT bursts have been done at DRES (Mellisen, 1974). The results of these tests have been used to provide blast loading input for structural analysis of lattice type masts also tested in the trials. On some of the trials there have been visible quantities of dust associated with the blast wave. In general the measured

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strains in the masts have agreed favorably in an individual field trial with the ones predicted from theoretical analysis based upon the blast loading input from the drag data averaged over several blast trials (Laidlaw, 1977). The influence of dust is difficult to determine and generally considered negligible.

Another area of interest in connection with moving particles in an air stream is the impingement of liquid drops on protective clothing and military equipment. The impaction efficiency and force, and the droplet distribution are all of interest. The study of these effects on transverse cylinders and spheres is useful in this application.

The purpose of this report is to describe numerical solutions to the equations of motion of particles in a moving air stream, with possible applications to both the effect on aerodynamic drag from the point of view of blast loading of structures and the interaction of droplets with spheres and cylinders from a chemical defence point of view. The mathematical techniques along with their associated computer programs are described herein. Also, the results are compared with experiments done at DRES (Gillespie and Gunter, 1957).

2. DEFINITION OF THE PROBLEM

A spherical particle flowing at free stream velocity far upstream of a spherical or transverse cylindrical solid target will not necessarily follow a streamline in the vicinity of the target where the radial and axial velocity components of the fluid may be changing markedly. A particle that just impinges on the outer circumference of the target was considered. All particles of the same diameter within an envelope generated by this limiting particle trajectory would hit the target, assuming that no particles collide with other particles reflected from the target.

All particles in the steady flow field far upstream were assumed to be travelling at the velocity of the fluid but the velocities of the particles will differ from the fluid velocity as the particles approach the target. This is due to inertial effects of the particles in

the flow field near the object. The velocity of a particle immediately before contact, and also the point of contact with the target, depend upon the position of the particle within the limiting envelope far upstream from which it travels to the target. These particles all have their momentum changed when they collide with the target and in the case of solid particles are deflected in a new direction. The total change in momentum is balanced by the drag force exerted by the particles on the target.

The basic problem was, therefore, to determine the envelope of particles hitting the target and the change in particle motion due to the presence of the target in the flow. Then the drag coefficient due to particles alone could be obtained.

3. EQUATIONS OF MOTION

The motion of an individual spherical particle has been shown (Batchelor, 1967) to be determined by the following ordinary differential equations:

$$\frac{d\bar{v}_y}{dT} = \frac{C_D \text{Re}(\bar{u}_y - \bar{v}_y)}{24K} \quad (\text{Eq. 1})$$

$$\frac{d\bar{v}_x}{dT} = \frac{C_D \text{Re}(\bar{u}_x - \bar{v}_x)}{24K} \quad (\text{Eq. 2})$$

where $\text{Re} = \text{Re}_0 [(\bar{u}_y - \bar{v}_y)^2 + (\bar{u}_x - \bar{v}_x)^2]^{1/2}$ (Eq. 3)

$$K = \frac{\sigma d^2 U}{18\mu L} \quad \text{particle inertia parameter} \quad (\text{Eq. 4})$$

$$\text{Re}_0 = \frac{U d \rho}{\mu} \quad \text{free stream Reynolds number} \quad (\text{Eq. 5})$$

The symbols are defined in the notation section near the front of this report and the basic geometry of the flow system is illustrated in Fig. 1.

Several assumptions were inherent in the development of Eq. 1 and Eq. 2 for calculating impaction efficiency and force due to a stream of particles, including,

- (a) uniform particle distribution,
- (b) no gravitational or electrostatic forces of consequence,
- (c) monodisperse spherical particles with diameter very small in relation to the target sphere or cylinder diameter, and
- (d) free stream flow that was steady, incompressible and irrotational.

The drag coefficient is a function of Reynolds number and was available in the form of definitive empirical equations (Davies, 1945). These equations are stated as follows:

$$Re = \frac{C_D Re^2}{24} - 2.3363 \times 10^{-4} (C_D Re^2)^2 + 2.0154 \times 10^{-6} (C_D Re^2)^3 - 6.9105 \times 10^{-9} (C_D Re^2)^4 \quad (\text{Eq. 6})$$

for $Re < 4$ or $C_D Re^2 < 140$

$$\log_{10} Re = -1.29536 + 9.86 \times 10^{-1} (\log_{10} C_D Re^2) - 4.6677 \times 10^{-2} (\log_{10} C_D Re^2)^3 + 1.1235 \times 10^{-3} (\log_{10} C_D Re^2)^3 \quad (\text{Eq. 7})$$

for $3 < Re < 10^4$ or $100 < C_D Re^2 < 4.5 \times 10^7$

4. AIR FLOW FIELD

The assumption was made that the air flow in front of the cylinder or sphere is given by classical hydrodynamics theory.

a) Cylinder

The equations of fluid velocity were derived from the stream function for ideal flow around a cylinder (Milne-Thomson, 1960). These were normalized to the free stream velocity and cylinder diameter and written as follows:

$$\bar{u}_x = 1 - \frac{\bar{x}^2 - \bar{y}^2}{\bar{r}^4} \quad (\text{Eq. 8})$$

$$\bar{u}_y = 1 - \frac{\bar{x} \bar{y}}{\bar{r}^4} \quad (\text{Eq. 9})$$

b) Sphere

For purposes of comparison of the results of the theoretical work reported herein to existing experimental data the flow field about a sphere on the axis of a circular tube was applied. The flow about a sphere in the absence of the tube was then readily available from this as a limiting case.

The flow velocity was derived (Mellisen et al., 1966) from the vector potential (Smythe, 1964). The velocity components are given in terms of a series solution. For a sphere diameter of 0.8 cm and tube diameter of 2.54 cm used in the experiments (Gillespie and Gunter, 1957) sufficient accuracy (Mellisen et al., 1966) was obtained by retaining three terms of the series.

The equations were

$$\frac{u_r}{U} = -\cos \theta \left[1 - \frac{2C_0}{3} \frac{C}{r}^3 - \frac{2A_0}{a} + \dots \right] \quad (\text{Eq. 10})$$

$$\frac{u_\theta}{U} = \sin \theta \left[1 + \frac{C_0}{3} \frac{C}{r}^3 - \frac{2A_0}{a} + \dots \right] \quad (\text{Eq. 11})$$

The constants C_0 , C and A_0 which are dependent upon the sphere and tube diameters (Smythe, 1964) are given as follows:

$$C_0 = 1.5401075$$

$$C = 1.0 \text{ (normalized sphere radius)}$$

$$A_0 = -C \left(\frac{C}{a} \right)^2 \frac{I(2)C_0}{9\pi}, \quad I(2) = 7.5098907$$

$$a = \frac{2.54}{0.8} C \text{ (normalized tube radius)}$$

u_θ and u_r are shown in Fig. 2.

Converting to rectangular co-ordinates gives

$$\bar{u}_x = -\frac{u_r}{U} \cos \theta + \frac{u_\theta}{U} \sin \theta \quad (\text{Eq. 12})$$

$$\bar{u}_y = \frac{u_r}{U} \sin \theta + \frac{u_\theta}{U} \cos \theta \quad (\text{Eq. 13})$$

The equation for flow around a sphere in the absence of the tube is given by letting the value of "a" approach infinity.

For $a \rightarrow \infty$, $C_o \rightarrow 1.5$ (Smythe, 1964)

$$\text{Eq. 10 becomes } \frac{u_r}{U} = -\cos \theta \left[1 - \left(\frac{L}{r} \right)^3 \right] \quad (\text{Eq. 14})$$

$$\text{Eq. 11 becomes } \frac{u_\theta}{U} = \sin \theta \left[1 + \frac{1}{2} \left(\frac{L}{r} \right)^3 \right] \quad (\text{Eq. 15})$$

Eqs. 14 and 15 are well known in ideal flow theory (Batchelor, 1967) and therefore serve as a partial check on the correctness of Eqs. 10 and 11.

5. VELOCITY CHANGE OF AN INDIVIDUAL PARTICLE

To calculate the drag force due to airborne particles, the velocity change of an individual particle due to the presence of the cylinder or sphere in the flow was first considered. The velocity change determined applied to both the cylindrical and spherical targets because the same geometry could be used for both (Fig. 3).

The motion considered concerned a spherical particle which starts far upstream within the envelope of particles which travel to the target, eventually hit it and are reflected by it in a new direction. The total change in direction of a particle which comes from a far upstream off-axis position y , and hits the target at a point defined by y' (Fig. 3), is represented by γ . For a spherical particle the angle of incidence, α , is equal to the angle of reflection. Then

$$\gamma = \left(\frac{\pi}{2} - \theta \right) + \alpha \quad (\text{Eq. 16})$$

where

$$\theta = \sin^{-1} \left(\frac{y'}{L} \right) = \tan^{-1} \left(\frac{y'}{\sqrt{L^2 - (y')^2}} \right) \quad (\text{Eq. 17})$$

and $\alpha + \beta = \frac{\pi}{2} - \theta$ (Eq. 18)

where $\beta = \tan^{-1} \left(\frac{v_y}{v_x} \right)$ (Eq. 19)

and v_x and v_y are the components of particle velocity just before impact with the target. Substituting the value of α obtained from Eq. 18 into Eq. 16 gives

$$\gamma = \pi - 2\theta - \beta \quad (\text{Eq. 20})$$

Substituting Eqs. 17 and 19 into Eq. 20 gives an equation of γ suitable for computation. Thus:

$$\gamma = \pi - 2 \tan^{-1} \left(\frac{y'}{\sqrt{1 - y'^2}} \right) - \tan^{-1} \left(\frac{v_y}{v_x} \right) \quad (\text{Eq. 21})$$

or in non-dimensional terms

$$\gamma = \pi - 2 \tan^{-1} \left(\frac{\bar{y}'}{\sqrt{1 - \bar{y}'^2}} \right) - \tan^{-1} \left(\frac{\bar{v}_y}{\bar{v}_x} \right) \quad (\text{Eq. 21a})$$

The component of velocity in the direction of free field flow immediately after particle reflection is

$$v_x' = v \cos \gamma \quad (\text{Eq. 22})$$

where $v = \sqrt{v_x^2 + v_y^2}$ (Eq. 23)

or in non-dimensional terms $\bar{v}_x' = \bar{v} \cos \gamma$ (Eq. 22a)

and $\bar{v} = \sqrt{\bar{v}_x^2 + \bar{v}_y^2}$ (Eq. 23a)

The total change of the component of velocity in the direction of free stream flow due to reflection from the target is then given by the following relationship:

$$\Delta v_x = v_x - v \cos \gamma \quad (\text{Eq. 24})$$

6. THE DRAG FORCE DUE TO PARTICLES ALONE

The force F_p of a stream of particles hitting a cylinder or sphere is related to the change in momentum which in general is given by the following relationship:

$$F_p = m' \Delta v_x \quad (\text{Eq. 25})$$

where m' is the total mass of particles having its momentum changed per unit time and Δv_x is its change of velocity in the free stream flow direction.

The quantity m' can be calculated using the following equation:

$$m' = \rho_p A_d v_{x0} \quad (\text{Eq. 26})$$

where ρ_p is the uniform particle density per unit volume of air far upstream, A_d is the far upstream cross sectional area of the envelope of particles which eventually hits the sphere or cylinder, and v_{x0} is the far upstream particle velocity which is assumed equal to the fluid velocity. Combining Eqs. 25 and 26 gives

$$F = \rho_p A_d v_{x0} \Delta v_x \quad (\text{Eq. 27})$$

Δv_x was not constant but was shown in the previous section to be a function of the off-axis, upstream starting location of an individual particle. This can be accounted for by integrating the velocity change over the range of starting locations across the particle envelope. Then the equation of force becomes

$$F = \rho_p v_{x0} \int_0^{A_d} \Delta v_x dA \quad (\text{Eq. 28})$$

where dA is an element of cross sectional area at location y .

Assuming that the particles do not interact with each other, the equation of drag force due to particles alone is then obtained in usable form by substituting Eq. 24 into Eq. 28 which gives the following equation:

$$F_p = \rho_p v_{x0} \int_0^{A_d} (v_x - v \cos \gamma) dA \quad (\text{Eq. 29})$$

7. THE DRAG COEFFICIENT

(a) Cylinder

For a transverse cylinder of unit length, Eq. 29 becomes

$$F_s = 2\rho_p v_{x0} \int_0^{y_c} (v_x - v \cos \gamma) dy \quad (\text{Eq. 30})$$

In non-dimensional terms this is written

$$\frac{F_s}{\rho_p U^2 L} = 2\bar{v}_{x0} \int_0^{\bar{y}_d} (\bar{v}_x - \bar{v} \cos \gamma) d\bar{y} \quad (\text{Eq. 31})$$

The drag coefficient is defined as follows:

$$C_D = \frac{p}{\frac{1}{2} \rho_p U^2} \quad (\text{Eq. 32})$$

where p is the average drag pressure (Schlichting, 1960).

The average drag pressure for a cylinder of unit length is given by the following equation:

$$p_c = \frac{F}{2L} \quad (\text{Eq. 33})$$

Substituting Eq. 33 into Eq. 32 and the resulting equation into Eq. 32 gives

$$C_{DC} = 2\bar{v}_{x0} \int_0^{\bar{y}_d} (\bar{v}_x - \bar{v} \cos \gamma) d\bar{y} \quad (\text{Eq. 34})$$

b) Sphere

For a sphere Eq. 29 becomes

$$F_s = 2\pi\rho_p v_{x0} \int_0^{y_c} (v_x - v \cos \gamma) y dy \quad (\text{Eq. 35})$$

In non-dimensional terms this is written

$$\frac{F_s}{\rho_p U^2 L^2} = 2\pi\bar{v}_{x0} \int_0^{\bar{y}_d} (\bar{v}_x - \bar{v} \cos \gamma) \bar{y} d\bar{y} \quad (\text{Eq. 36})$$

The drag pressure on the sphere is given by

$$p_s = \frac{F_s}{\pi L^2} \quad (\text{Eq. 37})$$

Substituting Eq. 36 into Eq. 37 and the resulting equation into Eq. 32 gives the drag coefficient for a sphere as follows:

$$C_{Ds} = 4\bar{v}_{x0} \int_0^{\bar{y}_d} (\bar{v}_x - \bar{v}' \cos \gamma) \bar{y} \, d\bar{y} \quad (\text{Eq. 38})$$

8. INTEGRATION METHOD FOR THE DRAG COEFFICIENT EQUATIONS

a) Cylinder

$$\text{Let } f(\bar{y}) = \bar{v}_x - \bar{v} \cos \gamma \quad (\text{Eq. 39})$$

Then Eq. 33 can be written

$$C_D = 2\bar{v}_{x0} \int_0^{\bar{y}_d} f(\bar{y}) \, d\bar{y} \quad (\text{Eq. 40})$$

$\int_0^{\bar{y}_d} f(\bar{y}) \, d\bar{y}$ was integrated numerically by dividing the upstream

cross sectional area into strips of equal width Δy , and calculating the contribution from each strip. These contributions were then summed as follows:

$$\int_0^{\bar{y}_d} f(\bar{y}) \, d\bar{y} = \frac{f(\bar{y}_1) + f(\bar{y}_n)}{2} + \sum_{i=2}^{i=n-1} f(\bar{y}_i) \Delta \bar{y} \quad (\text{Eq. 41})$$

where y_i increases with i from $\bar{y}' = 0$ to $\bar{y}_n = \bar{y}_d$.

b) Sphere

Using Eq. 39 in Eq. 38 gives the following equation for the drag coefficient of a sphere

$$C_{Ds} = 4\bar{v}_{x0} \int_0^{\bar{y}_d} f(\bar{y}) \bar{y} \, d\bar{y} \quad (\text{Eq. 42})$$

$\int_0^{\bar{y}_d} f(\bar{y}) \bar{y} d\bar{y}$ was integrated numerically by dividing the upstream

cross sectional area into concentric annuli of equal width $\Delta\bar{y}$ and calculating the contribution from each ring. These contributions were then summed as follows:

$$\int_0^{\bar{y}_d} f(\bar{y}) d\bar{y} = \sum_{i=1}^n f(\bar{y}_i) \bar{y}_i \Delta\bar{y} \quad (\text{Eq. 43})$$

where y_i increases with i from $\bar{y}_1 = \Delta\bar{y}$ to $\bar{y}_n = \bar{y}_d$

9. SOLUTION OF THE DRAG COEFFICIENT EQUATIONS

To solve Eq. 34 or Eq. 38 for the drag coefficient it was necessary to know the values of \bar{v}_x , \bar{v}' and γ in the range $0 \leq \bar{y} \leq \bar{y}_d$.

The first step was to find the value of \bar{y}_d which was the upper limit of the integral. This was done by an iterative procedure called the half interval method (Carnahan et al., 1969). The value of \bar{y} for the critical particle was estimated far upstream and the path followed to the target. The difference between the ordinate of the target path and the ordinate of the point on the actual path parallel to the tangent path was the miss criterion used. The direction of the tangent path was not known a priori but was assumed parallel to the actual path. The half interval method previously mentioned was applied to determine a better initial estimate. Then the path was followed to the target again for another calculation of miss distance. This process was repeated several times until sufficient accuracy was achieved. The plane of initial position of particles which was perpendicular to the flow direction was located far enough from the target so that free stream conditions prevailed. A distance of five target radii upstream of the target centre was considered adequate (Batchelor, 1967).

The path of an individual particle was determined step by step by applying a fourth order Runge-Kutta method (Carnahan et al., 1969) to

the equations of motion (Eqs. 1 and 2). The values of Re and K in these equations were easily determined for each new step by direct substitution of previously determined values into Eqs. 3, 4 and 5, but the value of $C_D Re$ in Eqs. 1 and 2 had to be calculated in each step by numerical solution of the definitive empirical equations (Eqs. 6 and 7). This was done using Newton's Method (Carnahan et al., 1969) for finding the zeros of a function. The values of \bar{u}_x and \bar{v}_y in Eqs. 1, 2 and 3 were calculated from Eqs. 8 and 9 for a cylindrical target and Eqs. 10, 11, 12 and 13 for a spherical target.

Once the value of \bar{y}_d had been determined the integration procedures described in Section 8 of this report were applied. The values of $f(\bar{y}_i)$ used in Eqs. 41 and 43 were obtained from Eq. 39. The quantities \bar{v} and γ used in the latter equation were calculated from Eqs. 23a and 21a respectively. The values of \bar{v}_x , \bar{v}_y and \bar{y}' used in the latter two equations were calculated by following a particle from its initial position to the cylindrical or spherical target using the previously described step by step procedure applied in determining the value of \bar{y}_d .

10. IMPACTION EFFICIENCY

The impaction efficiency was defined as the ratio of the cross sectional area of the far upstream envelope of particles which eventually hit the target to the cross sectional area of the target itself. For a transverse cylindrical target this is simply given by the value of \bar{y}_d . For a spherical target it is given by \bar{y}_d^2 .

11. COMPUTER PROGRAMS

Computer programs were written in Fortran IV for the DRES IBM 1130 computer to obtain solutions to the drag coefficient equations by the method described in Section 9 of this report. The complete programs, together with one set of results for each, are shown in Appendix A for the cylinder in free space and in Appendix B for the sphere in a tube or in free space (Appendix B). These programs are annotated so that the

functions of their various parts can be understood without further description. The application of the method described in Section 9, which was used in the programs, is straight forward with the exception of the step by step integration procedure near the target sphere or cylinder. This procedure is therefore explained as follows.

The particle motion was calculated in time steps, ΔT , until the particle was just one time step away from the target. Then the time increment size was decreased by a factor of ten and step by step integration continued until the particle was one new time step away from the target. At this point the time increment size was decreased by another factor of ten and the integration allowed to proceed until the target was reached. This method ensured that the position of the target and particle coincided within a maximum error given by the distance travelled during one percent of the original time step size, while allowing the particle to reach the proximity of the target in an adequate but small number of steps.

12. RESULTS

Drag coefficients and impaction efficiencies were calculated by means of the computer programs (Appendix A and B) from two main points of view. First, they were calculated using the particle sizes, fluid velocities and target configurations used in experiments done at Suffield many years ago (Gillespie and Gunter, 1957; 1959). This was done so that a comparison of the results from the theoretical calculation of drag due to particles in air could be made with existing information obtained from experiments. The results were obtained for a narrow range of particle sizes and fluid velocities and, correspondingly, a narrow range of inertia parameters and free stream particle Reynolds numbers. Next, calculations of impaction efficiencies and drag coefficients were done for a wide range of inertia parameters. The impaction efficiencies were compared with the results of other workers (Friedlander, 1977) but no results were available for comparison to the calculated drag coefficients over this

wide range of the inertia parameter. All the results previously mentioned are shown in Tables 1 and 2 and Fig. 4 - Fig. 9, along with plots of the calculated distribution of forces due to elastic reflection of particles from a cylinder (Fig. 10) and a sphere (Fig. 11). The latter two figures were plotted from the sample computer results shown with their corresponding programs in Appendix A and B. Further details explaining the significance of the tables and figures are described as follows.

The calculated results for the various particle sizes and fluid velocities used in the experiments done at Suffield (Gillespie and Gunter, 1957; 1959) are shown for a cylinder (Table 1) and for a sphere (Table 2). The sizes of these two targets also correspond to those in the experiments. The calculations were done for a 0.2 centimetre diameter cylinder in free space and a 0.8 centimetre sphere in a 2.54 centimetre tube. The tube which was used in all the experiments was included for the sphere since the velocity potential was readily available (Smythe, 1964). However, the effect of the presence of the tube on the potential flow and the final theoretical results was found to be negligible. Similarly, the effect of not including the tube in the potential flow for the cylinder is expected to be negligible.

A reason for tabulating the calculated results is to show clearly that the effect of particle size on the calculated drag coefficient for the sizes used in the experiments was negligibly small. This conclusion was also drawn from the experiments reported by Gillespie and Gunter (1957; 1959). The drag coefficients due to the middle size particles alone were plotted against target Reynolds number for the cylinder (Fig. 4) and for the sphere (Fig. 5). Also shown for the purpose of comparison of experiment to theory, described in the following section, are the drag coefficients due to air alone.

The impaction efficiencies for a wide range of the inertia parameter were plotted for cylinders (Fig. 6) and for spheres (Fig. 8). The cylinder results were plotted for $\phi = 1000$. The definition of ϕ

and the reason for its value choice are described as follows. The collection efficiency and also the drag coefficient are a function of two dimensionless groups, the inertial parameter, K , and the free stream particle Reynolds number, Re_0 . A new dimensionless group

$$\phi = \frac{Re_0^2}{K} \quad (\text{Eq. 44})$$

independent of particle size was introduced. According to the rules of dimensionless analysis this is permissible, but the efficiency is still determined by two groups which for convenience were chosen to be K and ϕ . The collection efficiencies were calculated by means of a mechanical analog and plotted for values of ϕ by other workers (Brun et al., 1953). The results for the middle value of ϕ from this work are also shown (Fig. 6) for comparison. The sphere results were plotted (Fig. 8) for an Re_0 value of 128. Again this choice was made for convenience of comparison to other work. The choice was the middle value of seven for which curves calculated from inviscid flow theory by Dorsch, Saper and Kadow are shown (Friedlander, 1977). The curve is also shown in Fig. 8.

The calculated drag coefficient due to particles alone were plotted for a wide range of inertia parameters for cylinders (Fig. 7) and for spheres (Fig. 9). In these two figures each curve was fitted by eye through several data points obtained by applying the computer programs (Appendix A and B) to various particle diameters for the cylinder case and various target diameters for the sphere case.

10. COMPARISON OF THEORETICAL RESULTS TO EXPERIMENTAL DATA

The experimental work previously done at Suffield (Gillespie and Gunter, 1957; 1959) indicated that the drag force of a sphere or cylinder is given by the following equation:

$$F = 1/2 \rho^* U^2 C_{De} A \quad (\text{Eq. 45})$$

$$\text{where} \quad \rho^* = \rho + \rho_p \quad (\text{Eq. 46})$$

and generally ρ and ρ_p are unequal. For Eq. 45 to be true, the drag coefficients due to particles alone carried by air and due to air alone must be equal. This is shown as follows. The total drag force consisted of two parts expressed by the following equation:

$$F_p + F_a = 1/2\rho_p U^2 A C_{Dp} + 1/2\rho U^2 A C_D \quad (\text{Eq. 47})$$

Comparison of Eq. 45 and 46 to Eq. 47 shows that

$$(\rho + \rho_p) C_{De} = \rho_p C_{Dp} + \rho C_D \quad (\text{Eq. 48})$$

C_{Dp} and C_D must be equal for Eq. 48 to be true.

The results obtained herein (Tables 1 and 2) and illustrated in Fig. 4 and 5 show that the calculated drag coefficients due to particles carried by air are considerably greater than the established drag coefficients due to air alone (Schlichting, 1960). The discrepancies between the experimental and calculated drag coefficients were accounted for by showing that the velocity of the particles in the experiments were considerably lower than the mean air velocity.

The particles which were introduced by Gillespie and Gunter into the air stream with zero velocity in the direction of air flow were accelerated along a horizontal section of 2.54 cm tube, 17 cm long, and a vertical section, 78 cm long, giving a total tube length of 95 cm between the starting point and the test section. Calculations of velocity as a function of distance for particles accelerated from rest were done to simulate Gillespie's experiments (Mellsen, in draft). The results for a travelled distance of 95 cm for the various mean air velocities and number median diameter used in the experiments are shown in Table 3. Also, the curves of velocity versus distance for the three diameters and one air velocity are illustrated in Fig. 14.

The particle velocities were difficult to calculate because the behavior of the particles travelling in the air stream around the corner in the tube was very complex. The velocity of the air in a straight cross section of the tube was zero at the walls and increased to the centre to 1.22 to 1.25 times the mean velocity (Prandtl and Tietjens,

1957). Therefore, the particle velocities were affected by the location of the particles in the tube cross section. This could not be accounted for because the time history of the location of the particles was not known. As a simplifying approximation, the mean air velocity was assumed to act on the particles over their length of travel in the tube which was also assumed vertical over its entire length. The experimental results indicate that the variation in velocities was less than this method of calculation shows. A mean value of drag force due to the presence of all particle sizes was used to offset this.

The drag coefficients which were calculated for particles with a free stream velocity equal to the mean air velocity (Table 1 and 2) were then adjusted to simulate the special conditions of the experiments as follows. The drag coefficients in the experiments were based on the mean air velocities as measured by a rotameter. The drag coefficients due to the particles travelling at lower velocities were adjusted to the mean air velocity by the following relationship for flow over the cylinder.

$$C_{DpU} = C_{Dc} \left(\frac{v_{rms}}{U} \right)^2 \quad (\text{Eq. 49})$$

This method was justified because, for the purpose of comparison, the calculated drag coefficients over the range of velocities and particle sizes used were sufficiently near a constant value (Table 1). All three particle sizes were assumed present in equal quantities in the air flow. Then, since the drag forces vary as the square of the velocity, the root mean square particle velocity, v_{rms} , was calculated for each mean fluid velocity (Table 3) and used in Eq. 49 to obtain a value for the drag coefficient due to dust alone at each mean air velocity (Table 4). The overall drag coefficients due to air and particles were then calculated for the dust concentrations used in the experiments, namely 2 and 5 kilograms per cubic metre of space. This was done by solving Eq. 48 for C_{De} . That is

$$C_{De} = \frac{\rho_p C_{Dc} + \rho C_D}{\rho + \rho_p} \quad (\text{Eq. 50})$$

The results are shown for each mean air velocity (Table 4) and plotted along with the drag coefficient for air alone (Fig. 12) as was done for the experiments of Gillespie and Gunter (1957; 1959).

A similar method was used to obtain the overall drag coefficients for the sphere with the exception that, as for the experimental results, they were corrected for the presence of the tube walls by the Landenburg correction (Gillespie and Gunter, 1957). That is, the drag coefficients due to particles alone were divided by the factor $1 + 2.4 L/a$ to obtain the corrected drag coefficient, C_{DL} . For the sphere and tube radii used, the factor is 1.756. Then, the overall drag coefficient for the sphere was obtained from

$$C_{De} = \frac{\rho_p C_{DL} + \rho C_D}{\rho + \rho_p} \quad (\text{Eq. 51})$$

The results are shown for each mean air velocity in Table 4, and plotted along with the drag coefficient for air alone in Fig. 13.

14. DISCUSSION

The equations of motion (Eq. 1 and 2) have never been proven experimentally (Friedlander, 1977) although they have been used to calculate deposition efficiencies for cylinders (Glauert, 1940). The mathematical model described herein used these equations to calculate collection efficiencies for cylinders which compare favorably (Fig. 6) with the results obtained using a differential analyzer (Brun et al., 1953). Also, the impaction efficiencies for spheres (Fig. 8) agree with solutions to the equations obtained by other workers (Friedlander, 1977).

In the work reported herein, the mathematical model for calculating impaction efficiency was extended to obtain the impaction forces due to particles in air flowing over spheres and cylinders. These results agree favorably with experiments previously done at Suffield (Gillespie and Gunter, 1957) when adjusted to the special conditions of the experiment. The experiments do support the theory, but the theoretical results

show that the results of the experiments are not applicable to the free field case of drag due to dusty air flowing over a cylinder or sphere.

The model could also be extended to blast loading problems. Since the effect of compressibility becomes important in these problems it would have to be accounted for. This could be done in the mathematical model by changing the air flow field equations to include it. The model could also be used to calculate the actual distributions of impaction velocities on cylinders (Fig. 10) and spheres (Fig. 11) in special cases which may have applications in chemical and nuclear defence.

15. CONCLUSIONS

A mathematical model was developed for calculating the impaction forces due to airborne particles on spheres and cylinders. The model can also be used for calculating impaction efficiencies, velocity distributions, and points of impact for a stream of airborne particles flowing over a sphere or cylinder. Hence, the drag coefficient for the particles on the sphere or cylinder can be determined.

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TABLE 1

COEFFICIENT OF DRAG ON A 0.2 CM CYLINDER FOR VARIOUS PARTICLE SIZES

	PARTICLE SIZE			AIR VELOCITY cm sec ⁻¹	P Re ₀ ² /K
	470μm	155μm	55μm		
Coefficient	2.367	2.362	2.333	700	3.99
of Drag due	2.367	2.361	2.327	560	3.19
to Particles	2.367	2.360	2.318	435	2.48
alone, C _{Dc}	2.367	2.357	2.300	294	1.67

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TABLE 2

COEFFICIENT OF DRAG ON A 0.8 CM SPHERE IN A 2.54 CM TUBE
FOR VARIOUS PARTICLE SIZES USING POTENTIAL FLOW

	PARTICLE SIZE			AIR VELOCITY cm sec ⁻¹	Re ₀ For 155μm
	470μm	155μm	55μm		
Coefficient	2.048	2.036	1.970	700	73.6
of Drag due	2.047	2.033	1.955	560	58.9
to Particles	2.047	2.030	1.934	426	44.8
alone, C _{Ds}	2.046	2.023	1.887	272	28.6

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TABLE 3
VELOCITY OF PARTICLES AT TARGET POSITION
ACCELERATED VERTICALLY UPWARD IN A TUBE FROM REST
95 cm UPSTREAM

PARTICLE DIAMETER cm	MEAN AIR VELOCITY IN TUBE cm sec ⁻¹	PARTICLE VELOCITY AT TARGET POSITION cm sec ⁻¹	RMS PARTICLE VELOCITY AT TARGET POSITION cm sec ⁻¹
0.0470	700	299	
0.0155	700	572	534
0.0055	700	664*	
0.0470	560	191	
0.0155	560	445	398
0.0055	560	527*	
0.0470	435	75*	
0.0155	435	325*	302
0.0055	435	405*	
0.0470	426	66	
0.0155	426	317	295
0.0055	426	396*	
0.0470	294	-	
0.0155	294	187*	188
0.0055	294	267*	
0.0470	272	-	
0.0155	272	166*	171
0.0055	272	245*	

* Upward terminal velocity reached

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TABLE 4

DRAG COEFFICIENT OF A 0.2 cm CYLINDER IN A 2.54 cm TUBE DUE TO AIR
CONTAINING EQUAL MASSES OF 0.0470, 0.0155 AND 0.0055 cm PARTICLES
CORRECTED FOR PARTICLE VELOCITY DEFICIENCY

U cm sec ⁻¹	C _{De}	C _D	U _{rms}	C _{Dpu}	C _{De} AIR + DUST		Re
					2 kg m ⁻³ Dust	5 kg m ⁻³ Dust	
700	2.354	1.00	534	1.369	1.23	1.30	949
560	2.352	1.05	398	1.188	1.14	1.16	759
435	2.348	1.15	302	1.132	1.14	1.14	590
294	2.341	1.25	188	0.957	1.07	1.01	399

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TABLE 5

DRAG COEFFICIENT OF A 0.8 cm SPHERE IN A 2.54 cm TUBE DUE TO AIR CONTAINING
EQUAL MASSES OF 0.0470, 0.155 AND 0.055 cm PARTICLES CORRECTED FOR
REAL FLUID VELOCITY AND PARTICLE VELOCITY DEFICIENCY

U cm sec ⁻¹	C _{DS}	C _D	U _{rms}	C _{DpU}	C _{DL}	C _{De}		Re
						2 kg m ⁻³ Dust	AIR + DUST 5 kg m ⁻³ Dust	
700	2.018	0.391	534	1.174	0.669	0.564	0.615	3796
560	2.012	0.396	398	1.016	0.579	0.510	0.543	3076
426	2.004	0.406	295	0.961	0.547	0.494	0.519	2310
272	1.985	0.433	171	0.785	0.447	0.442	0.444	1475

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APPENDIX A

COMPUTER PROGRAM FOR A CYLINDER

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PAGE 1

// JOB 1

LOG DRIVE CART SPEC CART AVAIL PHY DRIVE
0000 0205 0205 0000

V2 *11 ACTUAL 16K CONFIG 16K

// EJCT

PAGE 2

// FOR
*ONE WORD INTEGERS
*LIST ALL

SUBROUTINE SBM2RIG,TAU,DTAU,XK,REZ,UX,UY,XCDRE)

THIS SUBROUTINE CALCULATES PARTICLE MOTION DURING THE FINAL
INCREMENT OF TAU

DIMENSION G(4),DG(4)
N=0

CALL ON RUNGE KUTTA SUBROUTINE

A CONTINUE

N=N+1

CALL SBM22(4,G,DG,TAU,DTAU,IRUNG,M)

IF (IRUNG-1) GO TO 9,10

9 RE=REZ*((UY-G(2))**2+(UX-G(1))**2)**0.5

XCDRE=CDRE(RE)

DG(1)=(XCDRE/(24.0*XK))*(UX-G(1))

DG(2)=(XCDRE/(24.0*XK))*(UY-G(2))

DG(3)=G(1)

DG(4)=G(2)

GO TO 8

10 CONTINUE

N=N

C CALCULATE FLUID VELOCITY AT PARTICLE POSITION

RSQSQ=(G(3)**2+G(4)**2)**2

UX=1.0-(G(3)**2-G(4)**2)/RSQSQ

UY=-(G(3)*G(4))/RSQSQ

C INTEGRATE ACROSS ANOTHER STEP IF REQUIRED

IF(G(4) - 1.0)11,11,12

11 DELX = SORT(1.0 - G(4)**2)

GO TO 13

12 DELX = 0.0

13 HITS=G(3)+G(1)*1.0*DTAU+DELX

IF(HITS)8,8,18

18 CONTINUE

RETURN

END

VARIABLE ALLOCATIONS

DG(1)=0006-0000

RE(1)=0008

RSQSQ(1)=000A

DELX(1)=000C

HITS(1)=000E

M(1)=0012

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PAGE 3

IRING(I)=0013

STATEMENT ALLOCATIONS

R =0055 9 =C06A 1G =C0C0 11 =0104 12 =0115 13 =0119 18 =012E

FEATURES SUPPORTED
ONE WORD INTEGERS

CALLED SUBPROGRAMS

FSRR	FDVR	FSORT	FSUB	FADD	FADDX	FSUBX	FMPY	FMPYX	FDIV	FLDX	FSTD	FSTOX
FSR	FDV	FSO	FSB	FAD	FAD	FSB	FMP	FMP	FDD	FDD	FST	FST
FSR	FDV	FSO	FSB	FAD	FAD	FSB	FMP	FMP	FDD	FDD	FST	FST

REAL CONSTANTS

.500000F 00=0018 .240000E 02=001A .100000E 01=001C .000000E 00=001E .110000E 01=0020

INTEGER CONSTANTS

0=0022 1=0023 4=0024 2=0025

CORE REQUIREMENTS FOR SRM28
COMMON 0 VARIABLES 24 PROGRAM 280

RELATIVE ENTRY POINT ADDRESS IS 0026 (HEX)

END OF COMPILATION

// DUP

*STORE MS UA SRM28

CART ID 0205 DB ADDR 5F48 DB CNT 0015

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PAGE 4

// FOR
*ONE WORD INTEGERS
*LIST ALL
C

FUNCTION CDRE(RE)

C THIS FUNCTION COMPUTES THE PRODUCT OF DRAG COEFFICIENT
C AND REYNOLDS NUMBER FOR A SPHERE AS A FUNCTION OF
C REYNOLDS NUMBER
C

C CONSTANT COEFFICIENTS
C

A1=1./24.
A2=-2.3363#1.E-04
A3=2.0154#1.E-06
A4=-6.9105#1.E-09
R0=-1.29536
P1=9.86#1.E-01
P2=-4.6677#1.E-02
P3=1.1235#1.E-03

C CHOOSE THE APPROPRIATE POLYNOMIAL
C

C IFIRE-4.012#7.7
C

C INITIAL ESTIMATE
C

2 IFIRE - 0.00113#4.4

3 CDRE = 24.0

GO TO 30

4 X=24.*RE

C BEGIN NEWTON METHOD ITERATION
C

C CONTINUE
C

DO 6 ITER=1,20

FX=A1*X+A2*X**2+A3*X**3+A4*X**4-RE

FX=A1*X+A2*X**2+A3*X**3+A4*X**4-RE

DELX=FX/FPX

X=X-DELX

C CHECK FOR CONVERGENCE
C

EPS=1.E-06

IF(ABS(DELX/X))-EPS15,5,6

5 CDRE=X/RE

PAGE 5

GO TO 30
6 CONTINUE
GO TO 29

C INITIAL ESTIMATE

C
7 CD = 1.0
FLOG = 0.434294481903252
X=ALOG(CD*RE**2)*ELOG

C REGIN NEWTON METHOD ITERATION

C
DO 24 ITER=1,20
FX=RO+R1*X+R2*X**2+R3*X**3 - ALOGIRE)*ELOG
FPX=R1+2.*R2*X+3.*R3*X**2
DELX=FX/FPX
X=X-DELX

C CHECK FOR CONVERGENCE

C
FPS=1.E-06
IF(ABS(DELX/X)-FPS)22,22,24
22 CORE=10.*X/RE
GO TO 30
24 CONTINUE
29 WRITE(3,202)
30 RETURN

C FORMATS FOR OUTPUT STATEMENTS

C 202 FORMAT(16HC NO CONVERGENCE)

C

VARIABLE ALLOCATIONS

CORE(R)=0000
R1(R)=000C
DELX(R)=001R

A2(R)=0004
R3(R)=0010
CD(R)=001C

A3(R)=0006
X(R)=0012
ELOG(R)=001E

A4(R)=0008
FX(R)=0014
ITER(I)=0028

B0(R)=000A
FPX(R)=0016

STATEMENT ALLOCATIONS

202 =0057 2 =00A6 3
30 =01CF

=00R3 5 =00R3 4 =00AD 4 =00AD 3

=012B 6 =0133 7 =013E 22 =01C1 29 =01CA

=0186 24

=01CA

FEATURES SUPPORTED
ONE WORD INTEGERS

CALLED SUBPROGRAMS
FARS FALOG FAXR

FADD

FSUR

FMPY

FDIV

FLD

FSTO

FSBR

FAXI

SHRT

SCOMP

SNR

SUBIN

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PAGE 6

REAL CONSTANTS

.100000E 01=002A .240000E 02=002C .233630E 01=002E .100000E-03=0030 .201540E 01=0032 .100000E-05=0034
.691050E 01=0036 .100000E-08=0038 .129536E 01=003A .986000E 01=003C .100000E 03=003E .466770E 01=0040
.100000E-01=0042 .112350E 01=0044 .100000E-02=0046 .400000E 01=0048 .200000E 01=004A .300000E 01=004C
.434794E 00=004E .100000E 02=0050

INTFGER CONSTANTS

1=0052 20=0053 2=0054 3=0055 4=0056

CORE REQUIREMENTS FOR CDRE

COMMON 0 VARIABLES 42 PROGRAM 424

RELATIVE ENTRY POINT ADDRESS IS 0061 (HEX)

END OF COMPILATION

// DUP

*STORE XS UA CDRE

CART ID 0205 DB ADDR 5F60 DB CNT 0022

// FJECT

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PAGE 7
// FOR
*ONE WORD INTEGERS
*LIST ALL
SUBROUTINE SRM22(N,Y,F,X,H,IRUNG,M)
C
C FOURTH ORDER RUNGE KUTTA METHOD
C FOR N FIRST ORDER O.D.E.
C
C DIMENSION PHI(50),SAVY(50),Y(50),F(50)
C GO TO (2,3,4,5,6),M
C
C PASS 1
C
C 2 IRUNG=1
C RETURN
C
C PASS 2
C
C 3 DO 22 J=1,N
C SAVY(J)=Y(J)
C PHI(J)=F(J)
C 22 Y(J)=SAVY(J)+0.5*H*F(J)
C X=X+0.5*H
C IRUNG=1
C RETURN
C
C PASS 3
C
C 4 DO 23 J=1,N
C PHI(J)=PHI(J)+2.0*H*F(J)
C 33 Y(J)=SAVY(J)+0.5*H*F(J)
C IRUNG=1
C RETURN
C
C PASS 4
C
C 5 DO 44 J=1,N
C PHI(J)=PHI(J)+2.0*H*F(J)
C 44 Y(J)=SAVY(J)+H*F(J)
C X=X+0.5*H
C IRUNG=1
C RETURN
C
C PASS 5
C
C 6 DO 55 J=1,N
C 55 Y(J) = SAVY(J) + (PHI(J) + F(J))*H/6.0
C IRUNG=2
C RETURN
C
C END
```

PAGE 8

VARIABLE ALLOCATIONS
PHIR)=0062-0000 SAVYR)=00C6-0064 JII)=00C8

STATEMENT ALLOCATIONS

2 =0105 3 =0108 22 =011E 4 =0141 33 =0152 5 =016D 44 =017E 6 =019F 55 =01A3

FEATURES SUPPORTED
ONE WORD INTEGERS

CALLED SUBPROGRAMS

FADD FADDX FMPY FMPYX FDIV FLD FLDX FSTO FSTOX SUBSC SUBIN

REAL CONSTANTS

.500000F 00=00CA .200000E 01=00CC .600000E 01=00CE

INTEGER CONSTANTS

1=0000 2=00D1

CORE REQUIREMENTS FOR SRM22

COMMON 0 VARIABLES 202 PROGRAM 250

RELATIVE ENTRY POINT ADDRESS IS 00D2 (HEX)

END OF COMPILATION

// DUP

*STORE WS UA SRM22

CART ID 0205 DB ADDR 5F82 DB CNT 0012

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PAGE 9
// FOR
*ONE WORD INTEGERS
*LIST ALL
SUBROUTINE SBM29(G4LFT,G4RIT,SIGNL,DTAU,NIBP,NSBP,NX,XL,XK,REZ,
1G4ZFR)
C
C THIS SUBROUTINE CALCULATES THE
C IMPACTION EFFICIENCY OF A CIRCULAR CYLINDER
C
C DIMENSION G(4),DG(4)
C WRITE(3,200)
C WRITE(3,201)G4LFT,G4RIT,SIGNL,DTAU,NIBP,NSBP,NX
C HALF INTERVAL ITERATION FOR INITIAL G4 VALUE
C DO 47 ITER=1,NX
C
C SET AND PRINT INITIAL CONDITIONS
C
C N=0
C NSTFP=0
C TAU=0.0
C
C G(3)=XL
C G4ZFR=(G4LFT+G4RIT)/2.0
C G(4)=G4ZER
C RSQSO=(G(3)**2+G(4)**2)**2
C UX=1.0-(G(3)**2-G(4)**2)/RSQSO
C UY=-2.0*(G(3)*G(4))/RSQSO
C G(1)=UX
C G(2)=UY
C RE=REZ*((UY-G(2))**2+(UX-G(1))**2)**0.5
C XCDRE=CDRE*(RE)
C IP=ITER/NIBP*NIBP
C IF(IP-ITER)5,7,5
C
C 5 CONTINUE
C IF(ITER-1)6,7,6
C 6 CONTINUE
C IF(ITER-NX)8,7,8
C 7 CONTINUE
C WRITE(3,205)
C WRITE(3,203)ITER,G4LFT,G4ZER,G4RIT,TAU,G(1),G(2),G(3),G(4),UX,UY,
C 1XCDRE
C
C CALL ON RUNGE KUTTA SUBROUTINE
C
C 8 CONTINUE

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4=4+1
CALL SRM22(4,G,DG,TAU,DTAU,IRUNG,M)
IF(1RUMG-1)10,9,10
9 RF=REZ*((UY-G(2))**2-(UX-G(1))**2)**0.5
  XCDRE=CDRE(RF)
  DG(1)=(XCDRE/(24.0*XK1))*(UX-G(1))
  DG(2)=(XCDRE/(24.0*XK1))*(UY-G(2))
  DG(3)=G(1)
  DG(4)=G(2)
GO TO 8
10 CONTINUE
  M=0
  C
  C
  C
  CALCULATE FLUID VELOCITY AT PARTICLE POSITION
  RSQSO=(G(3)**2+G(4)**2)**2
  UX=1.0-(G(3)**2-G(4)**2)/RSQSO
  UY=-2.0*(G(3)*G(4))/RSQSO
  C
  C
  C
  PRINT SOLUTIONS
  C
  C
  IS = ITER/NIRP*NIRP
  IF(1S-1ITER)11,13,11
  11 CONTINUE
  IF(1ITER-1)12,13,12
  12 CONTINUE
  IF(1ITER-NX)16,13,16
  13 CONTINUE
  NSTP=NSTEP+1
  IF(NSTEP-NSRP)16,14,16
  14 CONTINUE
  NSTP=0
  TAY = TAU+0.0001
  WRITE(3,204)TAY,G(1),G(2),G(3),G(4),UX,UY,XCDRE
  C
  C
  C
  INTEGRATE ACROSS ANOTHER STEP IF REQUIRED
  16 CONTINUE
  IF(G(4)-1.0)17,17,18
  17 DELX=SORI(1.0-G(4)**2)
  GO TO 19
  18 DELX=0.0
  19 WITS=G(3)+G(1)*1.1*DTAU+DELX
  IF(WITS)9,8,20
  20 CONTINUE

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C CHANGE INCREMENT SIZE NEAR CYLINDER AND INTEGRATE FURTHER

C DTAV=DTAU/10.0

C CALL SPW28(G,TAU,DTAV,XK,REZ,UX,UY,XCDRE)

C PRINT SOLUTIONS

C IF(IIS-ITER)21,23,21
21 CONTINUE

C IF(ITER-1)22,23,22
22 CONTINUE

C IF(ITER-NX)24,23,24
23 CONTINUE

C WRITE(3,204)TAU,G(1),G(2),G(3),G(4),UX,UY,XCDRE
24 CONTINUE

C DTAV=DTAU/100.0

C CALL SPW28(G,TAU,DTAV,XK,REZ,UX,UY,XCDRE)

C PRINT SOLUTIONS

C IF(IIS-ITER)31,33,31
31 CONTINUE

C IF(ITER-1)32,33,32
32 CONTINUE

C IF(ITER-NX)34,33,34
33 CONTINUE

C WRITE(3,204)TAU,G(1),G(2),G(3),G(4),UX,UY,XCDRE
34 CONTINUE

C CALCULATE ORDINATE AT TANGENT POINT OF TANGENT PATH

C OPD = G(1)/SORT(G(1)**2 + G(2)**2)

C FIND INTERVAL HALF WITH THE SIGN CHANGE

C IF((G(4)-ORD)*SIGNL-0.0)45,45,46

45 GAZER

C GO TO 47

46 GAZER

47 CONTINUE

C EM = GAZER

C WRITE(3,207) FM

C RETURN

C

C FORMATS FOR OUTPUT STATEMENTS

200 FORMAT(1H0, 35X, 44H IMPACTION EFFICIENCY OF A CIRCULAR CYLINDER/

1 1H0)

201 FORMAT(10H0G4LEF = ,F10.6/ 10H G4RIT = ,F10.6/10H SIGML = ,

1 F3.0/ 10H 9TAU = ,F10.6/ 10H NIBP = ,I3/ 10H NSRP = ,I3/

2 10H NX = ,I3)

203 FORMAT(10H0ITER = ,I3/ 10H G4LEF = ,F10.6/ 10H G4ZER = ,

1 F10.6/ 10H G4RIT = ,F10.6/ 7H0 TAU, 11X, 4H6(1), 12X,

2 4H6(2), 12X, 4H6(3), 12X, 4H6(4), 14X, 2HUX, 14X, 2HUY,

3 12X, 4HCDRE /

4 1H0, F7.4, 4F16.6, 3F16.4)

204 FORMAT (1H, F7.4, 4F16.6, 3F16.4)

205 FORMAT (46H1THE MOTION OF A CRITICAL PARTICLE IS GIVEN BY)

207 FORMAT(30H0THE IMPACTION EFFICIENCY IS ,E10.4)

END

VARIABLE ALLOCATIONS

G(R) =C036-C000

RE(R) =C018

ORD(R) =0024

10HNG(I) =0030

DG(R) =C00E-C008

XCDRE(R) =001A

EM(R) =0026

IS(I) =0031

TAU(R) =0010

TAW(R) =001C

ITER(I) =002C

RSQSO(R) =0012

DELX(R) =001E

Y(I) =002D

UX(R) =0014

MTSR(R) =0020

NSTEP(I) =002E

UY(R) =0016

DTAM(R) =0022

IP(I) =002F

STATEMENT ALLOCATIONS

200 =C04D 201 =C06R 203 =C0A3 204 =C0E8 205 =C0F3 207 =C10C 5

C =C053 1C =C0A9 11 =C0FA 12 =C0B6 14 =C0B7 16 =C0B8 17 =C0B9 18 =C0BA 19 =C0BB 20 =C0BC 21 =C0BD 22 =C0BE 23 =C0BF 24 =C0C0 25 =C0C1 26 =C0C2 27 =C0C3 28 =C0C4 29 =C0C5 30 =C0C6 31 =C0C7 32 =C0C8 33 =C0C9 34 =C0CA 35 =C0CB 36 =C0CC 37 =C0CD 38 =C0CE 39 =C0CF 40 =C0D0 41 =C0D1 42 =C0D2 43 =C0D3 44 =C0D4 45 =C0D5 46 =C0D6 47 =C0D7 48 =C0D8 49 =C0D9 50 =C0DA 51 =C0DB 52 =C0DC 53 =C0DD 54 =C0DE 55 =C0DF 56 =C0E0 57 =C0E1 58 =C0E2 59 =C0E3 60 =C0E4 61 =C0E5 62 =C0E6 63 =C0E7 64 =C0E8 65 =C0E9 66 =C0EA 67 =C0EB 68 =C0EC 69 =C0ED 70 =C0EE 71 =C0EF 72 =C0F0 73 =C0F1 74 =C0F2 75 =C0F3 76 =C0F4 77 =C0F5 78 =C0F6 79 =C0F7 80 =C0F8 81 =C0F9 82 =C0FA 83 =C0FB 84 =C0FC 85 =C0FD 86 =C0FE 87 =C0FF 88 =C100 89 =C101 90 =C102 91 =C103 92 =C104 93 =C105 94 =C106 95 =C107 96 =C108 97 =C109 98 =C10A 99 =C10B 100 =C10C 101 =C10D 102 =C10E 103 =C10F 104 =C110 105 =C111 106 =C112 107 =C113 108 =C114 109 =C115 110 =C116 111 =C117 112 =C118 113 =C119 114 =C11A 115 =C11B 116 =C11C 117 =C11D 118 =C11E 119 =C11F 120 =C120 121 =C121 122 =C122 123 =C123 124 =C124 125 =C125 126 =C126 127 =C127 128 =C128 129 =C129 130 =C12A 131 =C12B 132 =C12C 133 =C12D 134 =C12E 135 =C12F 136 =C120 137 =C121 138 =C122 139 =C123 140 =C124 141 =C125 142 =C126 143 =C127 144 =C128 145 =C129 146 =C12A 147 =C12B 148 =C12C 149 =C12D 150 =C12E 151 =C12F 152 =C120 153 =C121 154 =C122 155 =C123 156 =C124 157 =C125 158 =C126 159 =C127 160 =C128 161 =C129 162 =C12A 163 =C12B 164 =C12C 165 =C12D 166 =C12E 167 =C12F 168 =C120 169 =C121 170 =C122 171 =C123 172 =C124 173 =C125 174 =C126 175 =C127 176 =C128 177 =C129 178 =C12A 179 =C12B 180 =C12C 181 =C12D 182 =C12E 183 =C12F 184 =C120 185 =C121 186 =C122 187 =C123 188 =C124 189 =C125 190 =C126 191 =C127 192 =C128 193 =C129 194 =C12A 195 =C12B 196 =C12C 197 =C12D 198 =C12E 199 =C12F 200 =C120 201 =C121 202 =C122 203 =C123 204 =C124 205 =C125 206 =C126 207 =C127 208 =C128 209 =C129 210 =C12A 211 =C12B 212 =C12C 213 =C12D 214 =C12E 215 =C12F 216 =C120 217 =C121 218 =C122 219 =C123 220 =C124 221 =C125 222 =C126 223 =C127 224 =C128 225 =C129 226 =C12A 227 =C12B 228 =C12C 229 =C12D 230 =C12E 231 =C12F 232 =C120 233 =C121 234 =C122 235 =C123 236 =C124 237 =C125 238 =C126 239 =C127 240 =C128 241 =C129 242 =C12A 243 =C12B 244 =C12C 245 =C12D 246 =C12E 247 =C12F 248 =C120 249 =C121 250 =C122 251 =C123 252 =C124 253 =C125 254 =C126 255 =C127 256 =C128 257 =C129 258 =C12A 259 =C12B 260 =C12C 261 =C12D 262 =C12E 263 =C12F 264 =C120 265 =C121 266 =C122 267 =C123 268 =C124 269 =C125 270 =C126 271 =C127 272 =C128 273 =C129 274 =C12A 275 =C12B 276 =C12C 277 =C12D 278 =C12E 279 =C12F 280 =C120 281 =C121 282 =C122 283 =C123 284 =C124 285 =C125 286 =C126 287 =C127 288 =C128 289 =C129 290 =C12A 291 =C12B 292 =C12C 293 =C12D 294 =C12E 295 =C12F 296 =C120 297 =C121 298 =C122 299 =C123 300 =C124 301 =C125 302 =C126 303 =C127 304 =C128 305 =C129 306 =C12A 307 =C12B 308 =C12C 309 =C12D 310 =C12E 311 =C12F 312 =C120 313 =C121 314 =C122 315 =C123 316 =C124 317 =C125 318 =C126 319 =C127 320 =C128 321 =C129 322 =C12A 323 =C12B 324 =C12C 325 =C12D 326 =C12E 327 =C12F 328 =C120 329 =C121 330 =C122 331 =C123 332 =C124 333 =C125 334 =C126 335 =C127 336 =C128 337 =C129 338 =C12A 339 =C12B 340 =C12C 341 =C12D 342 =C12E 343 =C12F 344 =C120 345 =C121 346 =C122 347 =C123 348 =C124 349 =C125 350 =C126 351 =C127 352 =C128 353 =C129 354 =C12A 355 =C12B 356 =C12C 357 =C12D 358 =C12E 359 =C12F 360 =C120 361 =C121 362 =C122 363 =C123 364 =C124 365 =C125 366 =C126 367 =C127 368 =C128 369 =C129 370 =C12A 371 =C12B 372 =C12C 373 =C12D 374 =C12E 375 =C12F 376 =C120 377 =C121 378 =C122 379 =C123 380 =C124 381 =C125 382 =C126 383 =C127 384 =C128 385 =C129 386 =C12A 387 =C12B 388 =C12C 389 =C12D 390 =C12E 391 =C12F 392 =C120 393 =C121 394 =C122 395 =C123 396 =C124 397 =C125 398 =C126 399 =C127 400 =C128 401 =C129 402 =C12A 403 =C12B 404 =C12C 405 =C12D 406 =C12E 407 =C12F 408 =C120 409 =C121 410 =C122 411 =C123 412 =C124 413 =C125 414 =C126 415 =C127 416 =C128 417 =C129 418 =C12A 419 =C12B 420 =C12C 421 =C12D 422 =C12E 423 =C12F 424 =C120 425 =C121 426 =C122 427 =C123 428 =C124 429 =C125 430 =C126 431 =C127 432 =C128 433 =C129 434 =C12A 435 =C12B 436 =C12C 437 =C12D 438 =C12E 439 =C12F 440 =C120 441 =C121 442 =C122 443 =C123 444 =C124 445 =C125 446 =C126 447 =C127 448 =C128 449 =C129 450 =C12A 451 =C12B 452 =C12C 453 =C12D 454 =C12E 455 =C12F 456 =C120 457 =C121 458 =C122 459 =C123 460 =C124 461 =C125 462 =C126 463 =C127 464 =C128 465 =C129 466 =C12A 467 =C12B 468 =C12C 469 =C12D 470 =C12E 471 =C12F 472 =C120 473 =C121 474 =C122 475 =C123 476 =C124 477 =C125 478 =C126 479 =C127 480 =C128 481 =C129 482 =C12A 483 =C12B 484 =C12C 485 =C12D 486 =C12E 487 =C12F 488 =C120 489 =C121 490 =C122 491 =C123 492 =C124 493 =C125 494 =C126 495 =C127 496 =C128 497 =C129 498 =C12A 499 =C12B 500 =C12C 501 =C12D 502 =C12E 503 =C12F 504 =C120 505 =C121 506 =C122 507 =C123 508 =C124 509 =C125 510 =C126 511 =C127 512 =C128 513 =C129 514 =C12A 515 =C12B 516 =C12C 517 =C12D 518 =C12E 519 =C12F 520 =C120 521 =C121 522 =C122 523 =C123 524 =C124 525 =C125 526 =C126 527 =C127 528 =C128 529 =C129 530 =C12A 531 =C12B 532 =C12C 533 =C12D 534 =C12E 535 =C12F 536 =C120 537 =C121 538 =C122 539 =C123 540 =C124 541 =C125 542 =C126 543 =C127 544 =C128 545 =C129 546 =C12A 547 =C12B 548 =C12C 549 =C12D 550 =C12E 551 =C12F 552 =C120 553 =C121 554 =C122 555 =C123 556 =C124 557 =C125 558 =C126 559 =C127 560 =C128 561 =C129 562 =C12A 563 =C12B 564 =C12C 565 =C12D 566 =C12E 567 =C12F 568 =C120 569 =C121 570 =C122 571 =C123 572 =C124 573 =C125 574 =C126 575 =C127 576 =C128 577 =C129 578 =C12A 579 =C12B 580 =C12C 581 =C12D 582 =C12E 583 =C12F 584 =C120 585 =C121 586 =C122 587 =C123 588 =C124 589 =C125 590 =C126 591 =C127 592 =C128 593 =C129 594 =C12A 595 =C12B 596 =C12C 597 =C12D 598 =C12E 599 =C12F 600 =C120 601 =C121 602 =C122 603 =C123 604 =C124 605 =C125 606 =C126 607 =C127 608 =C128 609 =C129 610 =C12A 611 =C12B 612 =C12C 613 =C12D 614 =C12E 615 =C12F 616 =C120 617 =C121 618 =C122 619 =C123 620 =C124 621 =C125 622 =C126 623 =C127 624 =C128 625 =C129 626 =C12A 627 =C12B 628 =C12C 629 =C12D 630 =C12E 631 =C12F 632 =C120 633 =C121 634 =C122 635 =C123 636 =C124 637 =C125 638 =C126 639 =C127 640 =C128 641 =C129 642 =C12A 643 =C12B 644 =C12C 645 =C12D 646 =C12E 647 =C12F 648 =C120 649 =C121 650 =C122 651 =C123 652 =C124 653 =C125 654 =C126 655 =C127 656 =C128 657 =C129 658 =C12A 659 =C12B 660 =C12C 661 =C12D 662 =C12E 663 =C12F 664 =C120 665 =C121 666 =C122 667 =C123 668 =C124 669 =C125 670 =C126 671 =C127 672 =C128 673 =C129 674 =C12A 675 =C12B 676 =C12C 677 =C12D 678 =C12E 679 =C12F 680 =C120 681 =C121 682 =C122 683 =C123 684 =C124 685 =C125 686 =C126 687 =C127 688 =C128 689 =C129 690 =C12A 691 =C12B 692 =C12C 693 =C12D 694 =C12E 695 =C12F 696 =C120 697 =C121 698 =C122 699 =C123 700 =C124 701 =C125 702 =C126 703 =C127 704 =C128 705 =C129 706 =C12A 707 =C12B 708 =C12C 709 =C12D 710 =C12E 711 =C12F 712 =C120 713 =C121 714 =C122 715 =C123 716 =C124 717 =C125 718 =C126 719 =C127 720 =C128 721 =C129 722 =C12A 723 =C12B 724 =C12C 725 =C12D 726 =C12E 727 =C12F 728 =C120 729 =C121 730 =C122 731 =C123 732 =C124 733 =C125 734 =C126 735 =C127 736 =C128 737 =C129 738 =C12A 739 =C12B 740 =C12C 741 =C12D 742 =C12E 743 =C12F 744 =C120 745 =C121 746 =C122 747 =C123 748 =C124 749 =C125 750 =C126 751 =C127 752 =C128 753 =C129 754 =C12A 755 =C12B 756 =C12C 757 =C12D 758 =C12E 759 =C12F 760 =C120 761 =C121 762 =C122 763 =C123 764 =C124 765 =C125 766 =C126 767 =C127 768 =C128 769 =C129 770 =C12A 771 =C12B 772 =C12C 773 =C12D 774 =C12E 775 =C12F 776 =C120 777 =C121 778 =C122 779 =C123 780 =C124 781 =C125 782 =C126 783 =C127 784 =C128 785 =C129 786 =C12A 787 =C12B 788 =C12C 789 =C12D 790 =C12E 791 =C12F 792 =C120 793 =C121 794 =C122 795 =C123 796 =C124 797 =C125 798 =C126 799 =C127 800 =C128 801 =C129 802 =C12A 803 =C12B 804 =C12C 805 =C12D 806 =C12E 807 =C12F 808 =C120 809 =C121 810 =C122 811 =C123 812 =C124 813 =C125 814 =C126 815 =C127 816 =C128 817 =C129 818 =C12A 819 =C12B 820 =C12C 821 =C12D 822 =C12E 823 =C12F 824 =C120 825 =C121 826 =C122 827 =C123 828 =C124 829 =C125 830 =C126 831 =C127 832 =C128 833 =C129 834 =C12A 835 =C12B 836 =C12C 837 =C12D 838 =C12E 839 =C12F 840 =C120 841 =C121 842 =C122 843 =C123 844 =C124 845 =C125 846 =C126 847 =C127 848 =C128 849 =C129 850 =C12A 851 =C12B 852 =C12C 853 =C12D 854 =C12E 855 =C12F 856 =C120 857 =C121 858 =C122 859 =C123 860 =C124 861 =C125 862 =C126 863 =C127 864 =C128 865 =C129 866 =C12A 867 =C12B 868 =C12C 869 =C12D 870 =C12E 871 =C12F 872 =C120 873 =C121 874 =C122 875 =C123 876 =C124 877 =C125 878 =C126 879 =C127 880 =C128 881 =C129 882 =C12A 883 =C12B 884 =C12C 885 =C12D 886 =C12E 887 =C12F 888 =C120 889 =C121 890 =C122 891 =C123 892 =C124 893 =C125 894 =C126 895 =C127 896 =C128 897 =C129 898 =C12A 899 =C12B 900 =C12C 901 =C12D 902 =C12E 903 =C12F 904 =C120 905 =C121 906 =C122 907 =C123 908 =C124 909 =C125 910 =C126 911 =C127 912 =C128 913 =C129 914 =C12A 915 =C12B 916 =C12C 917 =C12D 918 =C12E 919 =C12F 920 =C120 921 =C121 922 =C122 923 =C123 924 =C124 925 =C125 926 =C126 927 =C127 928 =C128 929 =C129 930 =C12A 931 =C12B 932 =C12C 933 =C12D 934 =C12E 935 =C12F 936 =C120 937 =C121 938 =C122 939 =C123 940 =C124 941 =C125 942 =C126 943 =C127 944 =C128 945 =C129 946 =C12A 947 =C12B 948 =C12C 949 =C12D 950 =C12E 951 =C12F 952 =C120 953 =C121 954 =C122 955 =C123 956 =C124 957 =C125 958 =C126 959 =C127 960 =C128 961 =C129 962 =C12A 963 =C12B 964 =C12C 965 =C12D 966 =C12E 967 =C12F 968 =C120 969 =C121 970 =C122 971 =C123 972 =C124 973 =C125 974 =C126 975 =C127 976 =C128 977 =C129 978 =C12A 979 =C12B 980 =C12C 981 =C12D 982 =C12E 983 =C12F 984 =C120 985 =C121 986 =C122 987 =C123 988 =C124 989 =C125 990 =C126 991 =C127 992 =C128 993 =C129 994 =C12A 995 =C12B 996 =C12C 997 =C12D 998 =C12E 999 =C12F 1000 =C120 1001 =C121 1002 =C122 1003 =C123 1004 =C124 1005 =C125 1006 =C126 1007 =C127 1008 =C128 1009 =C129 1010 =C12A 1011 =C12B 1012 =C12C 1013 =C12D 1014 =C12E 1015 =C12F 1016 =C120 1017 =C121 1018 =C122 1019 =C123 1020 =C124 1021 =C125 1022 =C126 1023 =C127 1024 =C128 1025 =C129 1026 =C12A 1027 =C12B 1028 =C12C 1029 =C12D 1030 =C12E 1031 =C12F 1032 =C120 1033 =C121 1034 =C122 1035 =C123 1036 =C124 1037 =C125 1038 =C126 1039 =C127 1040 =C128 1041 =C129 1042 =C12A 1043 =C12B 1044 =C12C 1045 =C12D 1046 =C12E 1047 =C12F 1048 =C120 1049 =C121 1050 =C122 1051 =C123 1052 =C124 1053 =C125 1054 =C126 1055 =C127 1056 =C128 1057 =C129 1058 =C12A 1059 =C12B 1060 =C12C 1061 =C12D 1062 =C12E 1063 =C12F 1064 =C120 1065 =C121 1066 =C122 1067 =C123 1068 =C124 1069 =C125 1070 =C126 1071 =C127 1072 =C128 1073 =C129 1074 =C12A 1075 =C12B 1076 =C12C 1077 =C12D 1078 =C12E 1079 =C12F 1080 =C120 1081 =C121 1082 =C122 1083 =C123 1084 =C124 1085 =C125 1086 =C126 1087 =C127 1088 =C128 1089 =C129 1090 =C12A 1091 =C12B 1092 =C12C 1093 =C12D 1094 =C12E 1095 =C12F 1096 =C120 1097 =C121 1098 =C122 1099 =C123 1100 =C124 1101 =C125 1102 =C126 1103 =C127 1104 =C128 1105 =C129 1106 =C12A 1107 =C12B 1108 =C12C 1109 =C12D 1110 =C12E 1111 =C12F 1112 =C120 1113 =C121 1114 =C122 1115 =C123 1116 =C124 1117 =C125 1118 =C126 1119 =C127 1120 =C128 1121 =C129 1122 =C12A 1123 =C12B 1124 =C12C 1125 =C12D 1126 =C12E 1127 =C12F 1128 =C120 1129 =C121 1130 =C122 1131 =C123 1132 =C124 1133 =C125 1134 =C126 1135 =C127 1136 =C128 1137 =C129 1138 =C12A 1139 =C12B 1140 =C12C 1141 =C12D 1142 =C12E 1143 =C12F 1144 =C120 1145 =C121 1146 =C122 1147 =C123 1148

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PAGE 13

RELATIVE ENTRY POINT ADDRESS IS 011E (HEX)

END OF COMPILATION

// DUP

*STORE WS UA SBN29
CART ID 0205 DB ADDR 5F94 DB CNT 0047

// EJECT

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PAGE 14
// FOR
*ONE WORD INTFGERS
*LIST ALL
SUBROUTINE SBM26(XL,GZER,DTAU,XK,REZ,PIX,NZER,NJBP)
C
C THIS SUBROUTINE CALCULATES THE MOTION OF PARTICLES
C IN A FLUID STREAM MOVING TOWARD A CIRCULAR CYLINDER AND
C CALCULATES THE FORCE OF PARTICLE IMPACT ON THE CYLINDER
C
C DIMENSION G(4),DG(4)
C DIMENSION YZER(500)
C
C SFT NUMBER OF INCREMENTS AT INITIAL POSITION
C
WRITE(3,200)
WRITE(3,201)NZER,NJBP
WRITE(3,202)
NCE=NZER+1
DELY=GZER/FLOAT(NZER)
FSUM=0.0
C
C STEPWISE INTEGRATION FOLLOWING PARTICLE POSITION
C
DO 40 ITER=1,NCE
C
C SET AND PRINT INITIAL CONDITIONS
C
M=0
TAU=C.0
G(3)=XL
YZER(ITER)=FLOAT(ITER-1)*DELY
GZER=YZER(ITER)
G(4)=GZER
RSOSQ=(G(3)**2+G(4)**2)**.2
UX=1.0-(G(3)**2-G(4)**2)/RSOSQ
UY=-2.0*(G(3)*G(4))/RSOSQ
UYZER=UX
UY=-(G(3)*G(4))/RSOSQ
G(1)=UX
G(2)=UY
C
C CALL ON RUNGE KUTTA SUBROUTINE
C
C
C CONTINUE
N=N+1
CALL SBM22(4,G,DG,DTAU,IRUNG,N)

```

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PAGE 15

IF(:RUNG-1110,9,10
9 RE=PEZ*((UY-G(2))**2+(UX-G(1))**2)**0.5
XCDPF=CPREIRE)

SG(1)=(XCDRE/(24.0*XX))*{(UX-G(1))

SG(2)=(XCDRE/(24.0*XX))*{(UY-G(2))

DG(3)=G(1)

DG(4)=G(2)

GO TO A

10 CONTINUE

M=0

C CALCULATE FLUID VELOCITY AT PARTICLE POSITION

C

PSOSQ=(G(3)**2+G(4)**2)**2

UX=1.0-(G(3)**2-G(4)**2)/PSOSQ

UY=-2.0*(G(3)*G(4))/PSOSQ

C INTEGRATE ACROSS ANOTHER STEP IF REQUIRED

C

IF(G(4) - 1.0)11,11,12

11 DELX = SORT(1.0 - G(4)**2)

GO TO 13

12 DELX = 0.0

13 HITS=G(3)+G(1)*1.1*DTAU+DELX

IF(HITS)R,8,18

18 CONTINUE

C CHANGE INCREMENT SIZE NEAR CYLINDER AND INTEGRATE FURTHER

C

DTAU=DTAU/10.0

CALL SPW28IG,TAU,DTAU,XK,REZ,UX,UY,XCDRE)

DTAU=DTAU/100.0

CALL SPW28IG,TAU,DTAU,XK,REZ,UX,UY,XCDRE)

C CO-ORDINATES, VELOCITY, AND PRESSURE DERIVATIVE AT CYLINDER

C

VX=G(1)

VY=G(2)

X=G(3)

Y=G(4)

V= SORT(VX**2+VY**2)

PI = 3.14159265358979323846264

GAMMA = PI - 2.0*ATAN(Y/SORT(1.0-Y**2)) - ATAN(VY/VX)

FY= UXZER*(VX- V*GOS(GAMMA))

IF(ITER-1124,25,24

24 CONTINUE

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```
IF(ITER-NCE)26,25,26
25 FSUM=FSUM+0.5*FY
GO TO 29
26 FSUM=FSUM+FY
29 CONTINUE
```

PRINT SOLUTIONS

```
IS = ITER/N.JBPEN.JBP
IF(IIS-ITER)31,33,31
```

31 IF(ITER-1)32,33,32
32 IF(ITER-NCE)34,33,34

CONTINUE

TAU = TAU+0.0001
WPRITE13,2031TAU,VX,VY,X,Y,UX,UY,EY

CONTINUE

ORAG COEFFICIENT OF CYLINDER DUE TO PARTICLE IMPACT

PRIME(3,204)PX
RETURN

FORMATS FOR OUTPUT STATEMENTS

200 FORMAT (55,1)THE MOTION OF THE PARTICLES AT THE CYLINDER POSITION I
IS GIVEN BY :

2001 FORMAT(10HONZER = ,I3,20X, 10H NARP = ,I3)

22071 FORMATT(7HQ 1 4H Y, 14X, 2-4UX, 14X, 2-4UY, 14X, 4H FY /1H) X, 12X, 12X,

1 14.4 2.32 14.4 2.40 14.4 2.48 14.4 2.56 14.4 2.64 14.4 2.72 14.4 2.80 14.4 2.88 14.4 2.96 14.4 3.04 14.4 3.12 14.4 3.20 14.4 3.28 14.4 3.36 14.4 3.44 14.4 3.52 14.4 3.60 14.4 3.68 14.4 3.76 14.4 3.84 14.4 3.92 14.4 4.00 14.4 4.08 14.4 4.16 14.4 4.24 14.4 4.32 14.4 4.40 14.4 4.48 14.4 4.56 14.4 4.64 14.4 4.72 14.4 4.80 14.4 4.88 14.4 4.96 14.4 5.04 14.4 5.12 14.4 5.20 14.4 5.28 14.4 5.36 14.4 5.44 14.4 5.52 14.4 5.60 14.4 5.68 14.4 5.76 14.4 5.84 14.4 5.92 14.4 6.00 14.4 6.08 14.4 6.16 14.4 6.24 14.4 6.32 14.4 6.40 14.4 6.48 14.4 6.56 14.4 6.64 14.4 6.72 14.4 6.80 14.4 6.88 14.4 6.96 14.4 7.04 14.4 7.12 14.4 7.20 14.4 7.28 14.4 7.36 14.4 7.44 14.4 7.52 14.4 7.60 14.4 7.68 14.4 7.76 14.4 7.84 14.4 7.92 14.4 8.00 14.4 8.08 14.4 8.16 14.4 8.24 14.4 8.32 14.4 8.40 14.4 8.48 14.4 8.56 14.4 8.64 14.4 8.72 14.4 8.80 14.4 8.88 14.4 8.96 14.4 9.04 14.4 9.12 14.4 9.20 14.4 9.28 14.4 9.36 14.4 9.44 14.4 9.52 14.4 9.60 14.4 9.68 14.4 9.76 14.4 9.84 14.4 9.92 14.4 10.00 14.4 10.08 14.4 10.16 14.4 10.24 14.4 10.32 14.4 10.40 14.4 10.48 14.4 10.56 14.4 10.64 14.4 10.72 14.4 10.80 14.4 10.88 14.4 10.96 14.4 11.04 14.4 11.12 14.4 11.20 14.4 11.28 14.4 11.36 14.4 11.44 14.4 11.52 14.4 11.60 14.4 11.68 14.4 11.76 14.4 11.84 14.4 11.92 14.4 12.00 14.4 12.08 14.4 12.16 14.4 12.24 14.4 12.32 14.4 12.40 14.4 12.48 14.4 12.56 14.4 12.64 14.4 12.72 14.4 12.80 14.4 12.88 14.4 12.96 14.4 13.04 14.4 13.12 14.4 13.20 14.4 13.28 14.4 13.36 14.4 13.44 14.4 13.52 14.4 13.60 14.4 13.68 14.4 13.76 14.4 13.84 14.4 13.92 14.4 14.00 14.4 14.08 14.4 14.16 14.4 14.24 14.4 14.32 14.4 14.40 14.4 14.48 14.4 14.56 14.4 14.64 14.4 14.72 14.4 14.80 14.4 14.88 14.4 14.96 14.4 15.04 14.4 15.12 14.4 15.20 14.4 15.28 14.4 15.36 14.4 15.44 14.4 15.52 14.4 15.60 14.4 15.68 14.4 15.76 14.4 15.84 14.4 15.92 14.4 16.00 14.4 16.08 14.4 16.16 14.4 16.24 14.4 16.32 14.4 16.40 14.4 16.48 14.4 16.56 14.4 16.64 14.4 16.72 14.4 16.80 14.4 16.88 14.4 16.96 14.4 17.04 14.4 17.12 14.4 17.20 14.4 17.28 14.4 17.36 14.4 17.44 14.4 17.52 14.4 17.60 14.4 17.68 14.4 17.76 14.4 17.84 14.4 17.92 14.4 18.00 14.4 18.08 14.4 18.16 14.4 18.24 14.4 18.32 14.4 18.40 14.4 18.48 14.4 18.56 14.4 18.64 14.4 18.72 14.4 18.80 14.4 18.88 14.4 18.96 14.4 19.04 14.4 19.12 14.4 19.20 14.4 19.28 14.4 19.36 14.4 19.44 14.4 19.52 14.4 19.60 14.4 19.68 14.4 19.76 14.4 19.84 14.4 19.92 14.4 20.00 14.4 20.08 14.4 20.16 14.4 20.24 14.4 20.32 14.4 20.40 14.4 20.48 14.4 20.56 14.4 20.64 14.4 20.72 14.4 20.80 14.4 20.88 14.4 20.96 14.4 21.04 14.4 21.12 14.4 21.20 14.4 21.28 14.4 21.36 14.4 21.44 14.4 21.52 14.4 21.60 14.4 21.68 14.4 21.76 14.4 21.84 14.4 21.92 14.4 22.00 14.4 22.08 14.4 22.16 14.4 22.24 14.4 22.32 14.4 22.40 14.4 22.48 14.4 22.56 14.4 22.64 14.4 22.72 14.4 22.80 14.4 22.88 14.4 22.96 14.4 23.04 14.4 23.12 14.4 23.20 14.4 23.28 14.4 23.36 14.4 23.44 14.4 23.52 14.4 23.60 14.4 23.68 14.4 23.76 14.4 23.84 14.4 23.92 14.4 24.00 14.4 24.08 14.4 24.16 14.4 24.24 14.4 24.32 14.4 24.40 14.4 24.48 14.4 24.56 14.4 24.64 14.4 24.72 14.4 24.80 14.4 24.88 14.4 24.96 14.4 25.04 14.4 25.12 14.4 25.20 14.4 25.28 14.4 25.36 14.4 25.44 14.4 25.52 14.4 25.60 14.4 25.68 14.4 25.76 14.4 25.84 14.4 25.92 14.4 26.00 14.4 26.08 14.4 26.16 14.4 26.24 14.4 26.32 14.4 26.40 14.4 26.48 14.4 26.56 14.4 26.64 14.4 26.72 14.4 26.80 14.4 26.88 14.4 26.96 14.4 27.04 14.4 27.12 14.4 27.20 14.4 27.28 14.4 27.36 14.4 27.44 14.4 27.52 14.4 27.60 14.4 27.68 14.4 27.76 14.4 27.84 14.4 27.92 14.4 28.00 14.4 28.08 14.4 28.16 14.4 28.24 14.4 28.32 14.4 28.40 14.4 28.48 14.4 28.56 14.4 28.64 14.4 28.72 14.4 28.80 14.4 28.88 14.4 28.96 14.4 29.04 14.4 29.12 14.4 29.20 14.4 29.28 14.4 29.36 14.4 29.44 14.4 29.52 14.4 29.60 14.4 29.68 14.4 29.76 14.4 29.84 14.4 29.92 14.4 30.00 14.4 30.08 14.4 30.16 14.4 30.24 14.4 30.32 14.4 30.40 14.4 30.48 14.4 30.56 14.4 30.64 14.4 30.72 14.4 30.80 14.4 30.88 14.4 30.96 14.4 31.04 14.4 31.12 14.4 31.20 14.4 31.28 14.4 31.36 14.4 31.44 14.4 31.52 14.4 31.60 14.4 31.68 14.4 31.76 14.4 31.84 14.4 31.92 14.4 32.00 14.4 32.08 14.4 32.16 14.4 32.24 14.4 32.32 14.4 32.40 14.4 32.48 14.4 32.56 14.4 32.64 14.4 32.

204 FORMATT THE DRAG COEFFICIENT OF THE CYLINDER DUE TO THE REFLECTION OF PARTICLES IS , F9.4)

VARIABLE ALLOCATIONS

[illegible]

STATEMENT ALLOCATIONS

[illegible]

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FEATURES SUPPORTED
ONE WORD INTEGERS

CALLED SUBPROGRAMS

SM22	CORE	FSORT	SM28	FATAN	FCOS	FAXB	FADD	FADDX	FSUB	FSUBX	FMPY	FMPYX	FDIV	FLD
FLY	FSTO	FSTOX	FSBR	FDVR	FAXI	FLOAT	SWRT	SCOMP	SIOF	SIOI	SUBSC	SNR	SUBIN	

REAL CONSTANTS

*100000E 00=0434	*100000E 01=0436	*200000E 01=0438	*500000E 00=043A	*2+0000E 02=043C	*110000E 01=043E
*100000E 02=0440	*100000E 03=0442	*31+159E 01=0444	*100000E-09=0446		

INTEGER CONSTANTS

3=044F	1=0449	0=044A	2=044B	4=044C
--------	--------	--------	--------	--------

CORE REQUIREMENTS FOR SM26

COMMON 0 VARIABLES 1076 PROGRAM 824

RELATIVE ENTRY POINT ADDRESS IS 0404 (HEX)

END OF COMPILATION

// DUP

*STORE 45 UA SM26 DB CNT 003B
CART ID 0205 DR ADDR 5FDR

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// FOR
*ONF WORD INTEGERS
*IOCS(CARD)
*IOCS(1132 PRINTER)
*LIST ALL

C ESTABLISH PHYSICAL PROPERTIES FOR CALCULATING IMPACTION EFFICIENCY

C ESTABLISH PARAMETERS FOR STEP BY STEP INTEGRATION AND HALF
C INTERVAL METHOD

C GALT AND GALT ARE LOWER AND UPPER ROUNDS RESPECTIVELY FOR
C STARTING LOCATION OF PARTICLE

C SIGNAL IS SIGN CORRECTION FOR HALF INTERVAL METHOD

C IN THIS PROBLEM IT IS -1.0

C DTAU IS THE TIME INCREMENT FOR STEP BY STEP INTEGRATION

C NSRP IS INTERVAL OF WRITTEN INTEGRATION STEPS

C *X IS NUMBER OF ITERATIONS USED TO DETERMINE PARTICLE STARTING
C POINT

1 READ(2,100)GALT,GALT,SIGNL,DTAU,NSRP,*X

C ESTABLISH PHYSICAL PROPERTIES FOR CALCULATING IMPACTION EFFICIENCY

C DC IS CYLINDER DIAMETER, CM

C DP IS PARTICLE DIAMETER, CM

C RHO IS FLUID DENSITY, GM/CC

C SIGMA IS PARTICLE DENSITY, GM/CC

C XMU IS ABSOLUTE VISCOSITY OF FLUID, POISE

C UF IS FREE STREAM VELOCITY, CM/SEC

READ(2,101)DC,DP,RHO,SIGMA,XMU,UF

C XL IS UPSTREAM STARTING POSITION FOR CALCULATING PARTICLE MOTION

READ(2,102)XL

REZ=RHO*DP*UF/XMU

XK=SIGMA*DP**2*UF/(9.*XMU*DC)

P = 9.*RHO**2*UF*DC/(XMU*SIGMA)

WRITE(3,200)

WRITE(3,201)

C XK IS INERTIAL PARAMETER CALLED STOKES NUMBER

C REZ IS FREE STREAM REYNOLDS NUMBER OF SPHERICAL PARTICLE

C P IS DIMENSIONLESS GROUP INDEPENDENT OF DROP SIZE

WRITE(3,202)XL,REZ,XK,P,DC,DP,RHO,SIGMA,XMU,UF

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C CALCULATE STARTING POSITION OF TANGENT PARTICLE

C CALL SRW29(IG4FT,G4RIT,SIGNL,DTAU,NIBP,NX,XL,XK,REZ,G4ZER)

C ESTABLISH NUMBER OF INCREMENTS FOR INTEGRATING PARTICLE FORCE

C NZER IS NUMBER OF INCREMENTS

C NJRP IS INTERVAL OF WRITTEN INCREMENTS

C READ(2,103)NZER,NJRP

C CALCULATE FORCE PRODUCED BY PARTICLES

C CALL SRW26(XL,G4ZER,DTAU,XK,REZ,PX,NZER,NJBP)

C CDAIR IS DRAG COEFFICIENT OF CYLINDER IN FREE AIR

C READ(2,104) CDAIR

C RECYL=RHO*DC*UF/XMU

C WRITE(3,204)RECYL

C WRITE(3,206)CDAIR

C READ(2,111)NSTOP

C IF(NSTOP)1,30,30

30 CALL EXIT

C FORMATS FOR INPUT AND OUTPUT STATEMENTS

100 FORMAT(10X,F10.7,20X,F10.7,19X,F3.0/ 10X,F10.7,20X,13,27X,I2/

1 10X,I2)

101 FORMAT(F10.5,F10.7,F10.6, F10.6,F10.7,F10.1)

102 FORMAT (F10.7)

103 FORMAT(I5,I5)

104 FORMAT(F10.6)

111 FORMAT(I5)

200 FORMAT(1H1, 34X, 51HTHE DRAG ON CYLINDERS IN A STREAM OF DUST-LAD

1EN AIR / 140)

201 FORMAT(28HTHE PHYSICAL PARAMETERS ARE)

202 FORMAT(10HXL = ,F10.7/10H REZ = ,E12.6/10H XK = ,

1 F12.6/10H P = ,E12.6/

2 10HDC = , F10.5/10H DP = ,F10.7/10H RHO = ,F10.6/

3 10H SIGMA = , F10.6/10H XMU = ,F10.7/10H UF = ,F10.1)

204 FORMAT(32HTHE TARGET REYNOLDS NUMBER IS ,E10.4)

206 FORMAT(61HTHE DRAG COEFFICIENT OF THE CYLINDER DUE TO THE AIR AL

10NE IS,F9.3)

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END

VARIABLE ALLOCATIONS

G4LFT(R) = 0000 G4RIT(R) = 0002 SIGNL(R) = 0004 DTAU(R) = 0006 DC(R) = 0008 DPLR = 000A
RHO(R) = 000C SIGMA(R) = 000E XMI(R) = 0010 UF(R) = 0012 XL(R) = 0014 REZIR = 0016
XK(R) = 0018 PIR = 001A G4ZER(R) = 001C PX(R) = 001E CDAT(R) = 0020 RECYLR = 0022
NIRP(I) = 0026 NSBP(I) = 0027 NX(I) = 0028 NZER(I) = 0029 NJBP(I) = 002A NSTOP(I) = 002B

STATEMENT ALLOCATIONS

100 = 0040 101 = 0041 102 = 0048 103 = 004A 104 = 004D 111 = 004F 200 = 0051 201 = 0073 202 = 0083 204 = 0093
206 = 00F6 1 = 011F 30 = 01D8

FEATURES SUPPORTED

ONE WORD INTEGERS

IOCS

CALLED SUBPROGRAMS

SRW29 SBW26 EMPY FDIY FLD FSTO FDVR FAXI CARDZ PRNTZ SRED SWRT SCOMP SF10 STOF
SI01

REAL CONSTANTS

.90000E 01=002C

INTEGER CONSTANTS

2=002E 3=002F

CORE REQUIREMENTS FOR

COMMON 0 VARIABLES 44 PROGRAM 430

END OF COMPILATION

// XFO

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THE DRAG ON CYLINDERS IN A STREAM OF DUST-LADEN AIR

THE PHYSICAL PARAMETERS ARE

XL = -5.0000009
 REZ = 0.735665E 02
 XK = 0.339462E 03
 P = 0.159429E 02
 DC = 0.80000
 DP = 0.015000
 RHO = 0.001213
 SIGMA = 2.600000
 XMU = 0.0001789
 UF = 700.0

IMPACTION EFFICIENCY OF A CIRCULAR CYLINDER

G4LFF = 0.000000
 G4RIT = 1.000000
 SIGPL = -1.
 DTAU = 0.100000
 NIAP = 10
 NSSP = 2
 NX = 20

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THE MOTION OF A CRITICAL PARTICLE IS GIVEN BY

ITER = 1
G4LEF = 0.000000
G4ZER = 0.500000
G4RIT = 1.000000

TAU	G(1)	G(2)	G(3)	G(4)	UX	UY	CDRE
0.0000	0.961180	0.007842	-5.000090	0.500000	0.9611	0.0078	24.0000
0.2000	0.961179	0.007842	-4.807763	0.501568	0.9581	0.0088	24.3728
0.4000	0.961177	0.007843	-4.615527	0.503136	0.9546	0.0099	25.2001
0.6000	0.961172	0.007844	-4.423291	0.504705	0.9508	0.0113	26.1397
0.8000	0.961164	0.007847	-4.231056	0.506274	0.9464	0.0129	27.1814
1.0000	0.961153	0.007851	-4.038823	0.507844	0.9415	0.0149	28.2857
1.2000	0.961138	0.007856	-3.846592	0.509415	0.9358	0.0172	29.3761
1.4000	0.961118	0.007864	-3.654366	0.510987	0.9293	0.0201	30.3616
1.6000	0.961093	0.007874	-3.462144	0.512560	0.9218	0.0236	31.2151
1.8000	0.961060	0.007887	-3.269928	0.514136	0.9131	0.0280	32.1351
2.0000	0.961019	0.007904	-3.077720	0.515715	0.9029	0.0334	34.0064
2.2000	0.960966	0.007928	-2.885521	0.517298	0.8908	0.0404	35.7737
2.4000	0.960898	0.007960	-2.693334	0.518887	0.8765	0.0493	37.7117
2.6000	0.960813	0.008002	-2.501165	0.520483	0.8595	0.0611	39.8650
2.8000	0.960734	0.008060	-2.309010	0.522089	0.8389	0.0767	42.2912
3.0000	0.960565	0.008141	-2.116882	0.523709	0.8139	0.0980	45.0651
3.2000	0.960386	0.008253	-1.924786	0.525348	0.7836	0.1276	48.2873
3.4000	0.960153	0.008415	-1.732731	0.527014	0.7467	0.1697	52.0961
3.6000	0.959848	0.008654	-1.540730	0.528720	0.7025	0.2314	56.6872
3.8000	0.959444	0.009018	-1.348799	0.530485	0.6515	0.3242	62.3423
4.0000	0.958911	0.009596	-1.156961	0.532343	0.5989	0.4682	69.4785
4.2000	0.958216	0.010551	-0.965246	0.534351	0.5638	0.6962	78.7198
4.3199	0.957729	0.011394	-0.850289	0.535669	0.5724	0.4465	73.4206
4.3250	0.957707	0.011418	-0.844543	0.535737	0.5739	0.4522	73.8589

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THE MOTION OF A CRITICAL PARTICLE IS GIVEN BY

ITER = 10
G4LFF = 0.919921
G4ZER = 0.920898
G4RIT = 0.921875

TAU	G(1)	G(2)	G(3)	G(4)	UX	UY	CDRE
0.0000	0.963851	0.013783	-5.000000	0.920898	0.9638	0.0137	24.0000
0.2000	0.963850	0.013783	-4.807229	0.923655	0.9612	0.0154	24.3607
0.4000	0.963848	0.013784	-4.614459	0.926411	0.9583	0.0174	25.1591
0.6000	0.963844	0.013787	-4.421689	0.929169	0.9551	0.0197	26.0637
0.8000	0.963837	0.013791	-4.228919	0.931926	0.9516	0.0224	27.0664
1.0000	0.963828	0.013798	-4.036151	0.934685	0.9476	0.0256	28.1339
1.2000	0.963816	0.013807	-3.843386	0.937446	0.9432	0.0294	29.1998
1.4000	0.963800	0.013819	-3.650624	0.940208	0.9383	0.0339	30.1789
1.6000	0.963780	0.013835	-3.457865	0.942973	0.9329	0.0395	31.0271
1.8000	0.963755	0.013857	-3.265111	0.945743	0.9268	0.0462	31.8578
2.0000	0.963723	0.013884	-3.072362	0.948517	0.9201	0.0545	33.3259
2.2000	0.963684	0.013921	-2.879621	0.951297	0.9126	0.0647	35.1617
2.4000	0.963637	0.013969	-2.686889	0.954086	0.9045	0.0775	36.9541
2.6000	0.963579	0.014033	-2.494166	0.956886	0.8958	0.0937	38.9166
2.8000	0.963509	0.014117	-2.301457	0.959700	0.8868	0.1162	41.0813
3.0000	0.963426	0.014229	-2.108763	0.962535	0.8780	0.1405	43.5126
3.2000	0.963328	0.014379	-1.916086	0.965395	0.8707	0.1745	46.2488
3.4000	0.963216	0.014583	-1.723432	0.968290	0.8668	0.2185	49.3641
3.6000	0.963094	0.014860	-1.530800	0.971233	0.8703	0.2752	52.9396
3.8000	0.962971	0.015242	-1.338194	0.974242	0.8878	0.3473	57.0675
4.0000	0.962872	0.015768	-1.145610	0.977361	0.9305	0.4354	61.8417
4.2000	0.962849	0.016487	-0.953039	0.980564	1.0152	0.5346	67.3322
4.4000	0.963000	0.017445	-0.760457	0.983954	1.1630	0.6257	73.5249
4.6000	0.963486	0.018646	-0.567813	0.987560	1.3876	0.6659	80.2095
4.8000	0.964318	0.019978	-0.375021	0.991422	1.6672	0.5890	86.8126
5.0000	0.966240	0.021135	-0.181953	0.995538	1.9132	0.3453	92.2867
5.1099	0.967489	0.022192	-0.075599	0.997873	1.9871	0.0752	94.9705
5.1249	0.967668	0.021300	-0.061086	0.998192	1.9924	0.0609	95.3191

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THE MOTION OF A CRITICAL PARTICLE IS GIVEN BY

ITER = 20
 G4LEF = 0.921587
 G4ZER = 0.921588
 G4RIT = 0.921589

TAU	G(1)	G(2)	G(3)	G(4)	UX	UY	CDRE
0.0000	0.963856	0.013792	-5.000000	0.921588	0.9638	0.0137	24.0000
0.2000	0.963855	0.013792	-4.807229	0.924346	0.9612	0.0154	24.3607
0.4000	0.963853	0.013793	-4.614457	0.927104	0.9583	0.0174	25.1520
0.6000	0.963849	0.013796	-4.421685	0.929863	0.9551	0.0197	26.0635
0.8000	0.963843	0.013800	-4.228915	0.932623	0.9516	0.0224	27.0662
1.0000	0.963834	0.013807	-4.036146	0.935384	0.9476	0.0256	28.1336
1.2000	0.963822	0.013816	-3.843379	0.938146	0.9432	0.0294	29.1994
1.4000	0.963806	0.013828	-3.650616	0.940910	0.9384	0.0340	30.1785
1.6000	0.963785	0.013844	-3.457856	0.943677	0.9329	0.0395	31.0267
1.8000	0.963760	0.013866	-3.265101	0.946448	0.9268	0.0462	31.8572
2.0000	0.963729	0.013893	-3.072351	0.949224	0.9201	0.0545	33.3243
2.2000	0.963690	0.013930	-2.879609	0.952006	0.9127	0.0647	35.1604
2.4000	0.963642	0.013978	-2.686875	0.954797	0.9045	0.0776	36.9526
2.6000	0.963585	0.014042	-2.494152	0.957599	0.8958	0.0937	38.9147
2.8000	0.963515	0.014126	-2.301441	0.960415	0.8869	0.1142	41.0849
3.0000	0.963432	0.014238	-2.108746	0.963251	0.8781	0.1406	43.5096
3.2000	0.963334	0.014368	-1.916069	0.966114	0.8708	0.1746	46.2449
3.4000	0.963222	0.014592	-1.723412	0.969011	0.8670	0.2185	49.3590
3.6000	0.963100	0.014869	-1.530780	0.971956	0.8706	0.2752	52.9328
3.8000	0.962977	0.015251	-1.338172	0.974966	0.8881	0.3472	57.0582
4.0000	0.962879	0.015776	-1.145586	0.978067	0.9308	0.4352	61.8289
4.2000	0.962857	0.016495	-0.953014	0.981291	1.0156	0.5341	67.3143
4.4000	0.963008	0.017452	-0.760430	0.984683	1.1633	0.6250	73.5000
4.6000	0.963495	0.018651	-0.567785	0.988290	1.3877	0.6649	80.1751
4.8000	0.964526	0.019980	-0.374991	0.992153	1.6666	0.5879	86.7667
5.0000	0.966245	0.021134	-0.181922	0.996270	1.9120	0.3445	92.2295
5.1999	0.967850	0.021306	-0.046538	0.999243	1.9950	0.0464	95.3180
5.1869	0.968415	0.021308	-0.001035	1.000241	1.9995	0.0010	95.5894

THE IMPACTION EFFICIENCY IS 0.9215E 00

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THE MOTION OF THE PARTICLES AT THE CYLINDER POSITION IS GIVEN BY

NZER = 12C

NJBP = 4

TAU	VX	VY	X	Y	UX	UY	FY
4.1690	0.955357	0.000000	-1.000526	0.000000	0.0010	0.0000	1.83428
4.1690	0.955364	0.000336	-1.000514	0.023886	0.0027	0.0238	1.83324
4.1710	0.955378	0.000785	-0.998553	0.055736	0.0064	0.0556	1.82856
4.1730	0.955417	0.001232	-0.996544	0.087586	0.0160	0.0871	1.82018
4.1760	0.955474	0.001677	-0.993535	0.119438	0.0298	0.1183	1.80807
4.1810	0.955537	0.002121	-0.988577	0.151292	0.0459	0.1495	1.79221
4.1860	0.955628	0.002561	-0.983570	0.183147	0.0679	0.1797	1.77265
4.1920	0.955739	0.002995	-0.977564	0.215004	0.0939	0.2094	1.74935
4.2000	0.955858	0.003428	-0.969602	0.246867	0.1226	0.2388	1.72231
4.2090	0.955999	0.003855	-0.960640	0.278733	0.1557	0.2674	1.69153
4.2190	0.956184	0.004289	-0.950676	0.310616	0.1931	0.2951	1.65693
4.2300	0.956354	0.004919	-0.939714	0.342495	0.2347	0.3216	1.61864
4.2420	0.956547	0.005340	-0.927748	0.374378	0.2807	0.3467	1.57661
4.2550	0.956763	0.005751	-0.914779	0.406266	0.3307	0.3702	1.53084
4.2700	0.956996	0.006154	-0.899855	0.438165	0.3843	0.3929	1.48131
4.2870	0.957249	0.006548	-0.882964	0.470077	0.4420	0.4145	1.42801
4.3050	0.957529	0.006930	-0.865068	0.501995	0.5039	0.4339	1.37096
4.3240	0.957769	0.007698	-0.846172	0.533943	0.5700	0.4508	1.30967
4.3450	0.958093	0.008059	-0.825305	0.565890	0.6400	0.4657	1.24505
4.3680	0.958439	0.008408	-0.802470	0.597853	0.7142	0.4784	1.17663
4.3930	0.958810	0.008745	-0.777668	0.629832	0.7925	0.4883	1.10441
4.4210	0.959137	0.009586	-0.749939	0.661867	0.8757	0.4958	1.02771
4.4510	0.959565	0.009888	-0.720228	0.693903	0.9627	0.4995	0.94782
4.4830	0.960020	0.010179	-0.688544	0.725957	1.0528	0.4987	0.86410
4.5190	0.960474	0.011027	-0.652960	0.758082	1.1480	0.4939	0.77584
4.5590	0.961009	0.011281	-0.613464	0.790235	1.2477	0.4839	0.68431
4.6040	0.961593	0.011538	-0.569094	0.822441	1.3523	0.4677	0.58882
4.6540	0.962233	0.012317	-0.519841	0.854754	1.4595	0.4435	0.48878
4.7130	0.962973	0.013062	-0.461844	0.887174	1.5733	0.4094	0.38473
4.7830	0.963851	0.013253	-0.393145	0.919734	1.6906	0.3612	0.27699
4.8730	0.964955	0.013895	-0.305038	0.952602	1.8135	0.2902	0.16438
4.9010	0.965300	0.013940	-0.277681	0.960891	1.8434	0.2665	0.13555

THE DRAG COEFFICIENT OF THE CYLINDER DUE TO THE REFLECTION OF PARTICLES IS 2.3435

THE TARGET REYNOLDS NUMBER IS 0.3796E 04

THE DRAG COEFFICIENT OF THE CYLINDER DUE TO THE AIR ALONE IS 1.000
// PAUS

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APPENDIX B

COMPUTER PROGRAM FOR A SPHERE IN A

TUBE OR IN FREE SPACE

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PAGE 1

// JOB T

LOG DRIVE CART SPEC CART AVAIL PHY DRIVE
0000 0305 0305 0001

V2 411 ACTUAL 16K CNFIG 16K

// EJECT

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PAGE 2

// FOR
 *ONE WORD INTEGERS

*LIST ALL

SUBROUTINE SBM34(G,UX,UY,ITURE)

C THIS SUBROUTINE CALCULATES THE FLOW ABOUT
 C A SPHERE IN A CIRCULAR TUBE FOR A SPHERE TO TUBE DIAMETER RATIO
 C OF 0.8/2.54 OR FOR A SPHERE IN FREE SPACE.

C DIMENSION G(4)

IF(ITURE)1,1,2

1 RSQ = G(3)**2+G(4)**2

UX = 1.0 - 1.0/RSQ**1.5

UY = 1.5*G(3)*G(4)/RSQ**2.5

GO TO 3

2 R = SORT(G(3)**2 + G(4)**2)

COST = -G(3)/R

SINT = G(4)/R

DC = 0.8

C = 1.0

A = (2.54/DC)*C

S2 = 7.5098907

CZERO = 1.5401075

PI = 3.14159265358979323846264

AZERO = C*(C/A)**2*S2*CZERO/(9.0*PI)

FT1 = CZERO*C**3/(3.*R**3)

FT2 = 2.0*AZERO/A

UT = SINT*(1.0+FT1-FT2)

FR1 = 2.0*CZERO*C**3/(3.*R**3)

FR2 = FT2

UR = COST*(1.0-FR1-FR2)

UX = -UR*COST + UT*SINT

UY = UR*SINT + UT*COST

3 CONTINUE

RETURN

END

VARIABLE ALLOCATIONS

RSQ(R) = 0000

A(R) = 000C

FT2(R) = 0018

R(R) = 0002

S2(R) = 000E

UT(R) = 001A

COST(R) = 0004

CZERO(R) = 0010

FR1(R) = 001C

SINT(R) = 0006

PI(R) = 0012

FR2(R) = 001E

DC(R) = 0008

AZERO(R) = 0014

UR(R) = 0020

C(R) = 000A

FT1(R) = 0016

STATEMENT ALLOCATIONS

1 = 0059 2 = 00A3 3 = 016E

FEATURES SUPPORTED

ONE WORD INTEGERS

PAGE 3

CALLFD SURPROGRAMS

FSORT	FAXB	FADD	FSUB	FMPY	FMPYX	FDIV	FLD	FLDX	FSTO	FSBR	FDVR	FAXI	SNR	SUBIN
REAL CONSTANTS														
.100000F	G1=002R		.150000E	01=002A	.250000E	01=002C	.800000E	00=002E	.254000E	01=0030	.750989E	01=0032		
.15401CF	01=0034		.314159E	01=0036	.900000E	01=0038	.500000E	01=003A	.200000E	01=003C				

INTEGER CONSTANTS

2=003E 3=003F

CORF REQUIREMENTS FOR SBM34

COMMON 0 VARIABLES 40 PROGRAM 328

RELATIVE ENTRY POINT ADDRESS IS 0040 (HEX)

END OF COMPILATION

// DUP

*STORE WS UA SBM34

CART ID 0305 DB ADDR 5A0A DB CNT 0018

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// FOR
*ONE WORD INTEGERS
*LIST ALL

C FUNCTION CDRE(RE)

C THIS FUNCTION COMPUTES THE PRODUCT OF DRAG COEFFICIENT
C AND REYNOLDS NUMBER FOR A SPHERE AS A FUNCTION
C OF REYNOLDS NUMBER LESS THAN 10000.
C

A1=1./24.
A2=-2.3363*1.E-04
A3=2.0154*1.E-06
A4=-6.9105*1.E-09
R0=-1.29536
R1=9.86*1.E-01
R2=-4.6677*1.E-02
R3=1.1235*1.E-03

C CHOOSE THE APPROPRIATE POLYNOMIAL

C IF(RE-4.0)2,7,7

C INITIAL ESTIMATE

2 IF(RE-0.0001)3,4,4
3 CDRE = 24.0
GO TO 30
4 X=24.*RE

C BEGIN NEWTON METHOD ITERATION

C CONTINUE

DO 6 ITER=1,20

FX=A1*X+A2*X**2+A3*X**3+A4*X**4-RE
FPX=A1+2.*A2*X+3.*A3*X**2+4.*A4*X**3
DELX=FPX/FPX
X=X-DELX

C CHECK FOR CONVERGENCE

C EPS=1.E-06
IF(ABS(DELX/X)-EPS)5,5,6

5 CDRE=X/RE

GO TO 30

6 CONTINUE

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PAGE 5

GO TO 29

INITIAL ESTIMATE

CD = 1.0

ELOG = 0.434294481903252

X=ALOG(CD=RE**2)*ELOG

REGIN NEWTON METHOD ITERATION

DO 24 ITER=1,20

FX=RO+RI*X+B2*X**2+33*X**3 - ALOG(RE)*ELOG

FPX=B1+2.*B2*X+3.*B3*X**2

DELX=FX/FPX

X=X-DELX

CHECK FOR CONVERGENCE

EPS=1.E-06

IF(ABS(DELX/X)-EPS)22,22,24

22 CDRE=10.**X/RE

GO TO 30

24 CONTINUE

29 WRITE(3,202)

30 RETURN

FORMATS FOR OUTPUT STATEMENTS

202 FORMAT(16H0 NO CONVERGENCE)

END

VARIABLE ALLOCATIONS

CDRE(1)=0000

B1(1)=0000

DELX(1)=0018

A1(1)=0002

B2(1)=000E

EPS(1)=001A

A2(1)=0004

B3(1)=0010

CD(1)=001C

A3(1)=0006

X(1)=0012

ELOG(1)=0C1E

A4(1)=0006

FX(1)=0014

ITER(1)=0028

B0(1)=000A

FPX(1)=0016

STATEMENT ALLOCATIONS

202 =0059 2 =00AR 3 =00AF 4 =0085 5 =012D 6 =0143 7 =0188 22 =01C3 29 =01CC

30 =01D0

FEATURES SUPPORTED

ONE WORD INTEGERS

CALLED SURPROGRAMS

FARS FALOG FAXB FADD FSUB FMPY FDIV FLD FSTO FSBR FAXI SWRT SCOMP SNR SUBIN

REAL CONSTANTS

.100000F 01=002A .240000E 02=002C .233630E 01=002E .100000E-03=0030 .201540E 01=0032 .100000E-05=0034

PAGE 6

.691050F 01=0036 .100000E-08=0038 .129536E 01=003A .986000E 01=003C .466770E 01=0040
.100000E-01=0042 .112350E 01=0044 .100000E-02=0046 .400000E 01=0048 .200000E 01=004C
.300000E 01=004E .634294E 00=0050 .100000E 02=0052

INTEGER CONSTANTS

1=0054 20=0055 2=0056 3=0057 4=0058

CORE REQUIREMENTS FOR CDRE

COMMON 0 VARIABLES 42 PROGRAM 426

RELATIVE ENTRY POINT ADDRESS IS 0063 (HEX)

END OF COMPILATION

// DUP

*STORE WS UA CDRE

CART ID 0305 DB ADDR 5A25 DB CNT 0022

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PAGE 7

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// FOR
*ONE WORD INTEGERS
*LIST ALL
SURROUTINE SRM22(IN,Y,F,X,H,IRUNG,M)
C
C FOURTH ORDER RUNGE KUTTA METHOD
C FOR N FIRST ORDER O.D.E.
C DIMENSION PH(50),SAVY(50),Y(50),F(50)
C
C GO TO (2,3,4,5,6),M
C
C PASS 1
C
C 2 IRUNG=1
C RETURN
C
C PASS 2
C
C 3 DO 22 J=1,N
C   SAVY(J)=Y(J)
C   PH(J)=F(J)
C   22 Y(J)=SAVY(J)+0.5*H*F(J)
C   X=X+0.5*H
C   IRUNG=1
C   RETURN
C
C 4 DO 23 J=1,N
C   PH(J)=PH(J)+2.0*F(J)
C   33 Y(J)=SAVY(J)+0.5*H*F(J)
C   IRUNG=1
C   RETURN
C
C PASS 4
C 5 DO 44 J=1,N
C   PH(J)=PH(J)+2.0*F(J)
C   44 Y(J)=SAVY(J)+H*F(J)
C   X=X+0.5*H
C   IRUNG=1
C   RETURN
C PASS 5
C 6 DO 55 J=1,N
C   55 Y(J) = SAVY(J) + (PH(J) + F(J))*H/6.0
C   IRUNG=2
C   RETURN
C
C END
```

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PAGE 8

VARIABLE ALLOCATIONS
PFI(R)=0062-0000

SAVY(R)=00C6-0064

JII)=00C8

STATEMENT ALLOCATIONS
2 =0105 3 =0108 22 =011E 4 =0141 33 =0152 5 =016D 44 =017E 6 =019F 55 =01A3

FEATURES SUPPORTED
ONE WORD INTEGERS

CALLED SUBPROGRAMS
FADD FADDX FMPY FMPYX FD:V FLD FLDX FSTO FSTOX SUBSC SUBIN

REAL CONSTANTS
*500000E 00=00CA

*200000E 01=00CC

INTEGER CONSTANTS
1=0000 2=0001 *600000E 01=00CE

CORE REQUIREMENTS FOR SRM22
COMMON 0 VARIABLES 202 PROGRAM 250

RELATIVE ENTRY POINT ADDRESS IS 00D2 (HEX)

END OF COMPILATION

// DUP

*STORE WS UA SRM22

CART ID 0305 DR ADDR 5A47 DB CNT 0C12

// EJECT

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// FOR
*ONE WORD INTFGERS
*LIST ALL

SUBROUTINE SBM32(G,TAU,DTAW,XK,REZ,UX,UY,XCDRE)

THIS SUBROUTINE CALCULATES PARTICLE MOTION DURING THE FINAL
INCREMENT OF TAU

DIMENSION G(4),DG(4)
N=N

CALL ON RUNGE KUTTA SUBROUTINE

CONTINUE

N=N+1
CALL SBM22(4,G,DG,TAU,DTAW,IRUNG,N)

IF(IRUNG-1)10,9,10
9 RE=REZ*(UY-G(2))*2+(UX-G(1))*2**0.5
XCDRE=CDRE(RE)

DG(1)=(XCDRE/(24.0*XK))*(UX-G(1))

DG(2)=(XCDRE/(24.0*XK))*(UY-G(2))

DG(3)=G(1)

DG(4)=G(2)

GO TO 8

10 CONTINUE

N=N

C CALCULATE FLUID VELOCITY AT PARTICLE POSITION

C CALL SBM34 (G,UX,UY,ITUBE)

C INTEGRATE ACROSS ANOTHER STEP IF REQUIRED

IF(G(4) - 1.0)11,11,12

11 DELX = SORT(1.0 - G(4)**2)

GO TO 13

12 DELX = 0.0

13 HITS=G(3)+G(1)*1.1*DTAW+DELX

IF(HITS)8,8,12

12 CONTINUE

RETURN

END

VARIABLE ALLOCATIONS

DGIR 1=0006-0000

ITUBE(1)=0012

REIR 1=0008

DELX(R)=000A

HITS(R)=000C

N(1)=0010

IRUNG(1)=0011

STATEMENT ALLOCATIONS
8 20050 9 2006

FEATURES SUPPORTED	10	11	12	13	18
ONE WORD INTEGERS					

CALLLED SURPROGRAMS

SBM22	CORE	SBM34
FDVR	FA	SUBIN

REAL CONSTANTS

INTEGERS		CONSTANTS	
0=0000	00=0000	0=0000	00=0000
1=0001	01=0001	1=0001	01=0001
2=0002	02=0002	2=0002	02=0002
3=0003	03=0003	3=0003	03=0003
4=0004	04=0004	4=0004	04=0004
5=0005	05=0005	5=0005	05=0005
6=0006	06=0006	6=0006	06=0006
7=0007	07=0007	7=0007	07=0007
8=0008	08=0008	8=0008	08=0008
9=0009	09=0009	9=0009	09=0009
10=0010	10=0010	10=0010	10=0010
11=0011	11=0011	11=0011	11=0011
12=0012	12=0012	12=0012	12=0012
13=0013	13=0013	13=0013	13=0013
14=0014	14=0014	14=0014	14=0014
15=0015	15=0015	15=0015	15=0015
16=0016	16=0016	16=0016	16=0016
17=0017	17=0017	17=0017	17=0017
18=0018	18=0018	18=0018	18=0018
19=0019	19=0019	19=0019	19=0019
20=0020	20=0020	20=0020	20=0020
21=0021	21=0021	21=0021	21=0021
22=0022	22=0022	22=0022	22=0022
23=0023	23=0023	23=0023	23=0023
24=0024	24=0024	24=0024	24=0024
25=0025	25=0025	25=0025	25=0025
26=0026	26=0026	26=0026	26=0026
27=0027	27=0027	27=0027	27=0027
28=0028	28=0028	28=0028	28=0028
29=0029	29=0029	29=0029	29=0029
30=0030	30=0030	30=0030	30=0030
31=0031	31=0031	31=0031	31=0031
32=0032	32=0032	32=0032	32=0032
33=0033	33=0033	33=0033	33=0033
34=0034	34=0034	34=0034	34=0034
35=0035	35=0035	35=0035	35=0035
36=0036	36=0036	36=0036	36=0036
37=0037	37=0037	37=0037	37=0037
38=0038	38=0038	38=0038	38=0038
39=0039	39=0039	39=0039	39=0039
40=0040	40=0040	40=0040	40=0040
41=0041	41=0041	41=0041	41=0041
42=0042	42=0042	42=0042	42=0042
43=0043	43=0043	43=0043	43=0043
44=0044	44=0044	44=0044	44=0044
45=0045	45=0045	45=0045	45=0045
46=0046	46=0046	46=0046	46=0046
47=0047	47=0047	47=0047	47=0047
48=0048	48=0048	48=0048	48=0048
49=0049	49=0049	49=0049	49=0049
50=0050	50=0050	50=0050	50=0050
51=0051	51=0051	51=0051	51=0051
52=0052	52=0052	52=0052	52=0052
53=0053	53=0053	53=0053	53=0053
54=0054	54=0054	54=0054	54=0054
55=0055	55=0055	55=0055	55=0055
56=0056	56=0056	56=0056	56=0056
57=0057	57=0057	57=0057	57=0057
58=0058	58=0058	58=0058	58=0058
59=0059	59=0059	59=0059	59=0059
60=0060	60=0060	60=0060	60=0060
61=0061	61=0061	61=0061	61=0061
62=0062	62=0062	62=0062	62=0062
63=0063	63=0063	63=0063	63=0063
64=0064	64=0064	64=0064	64=0064
65=0065	65=0065	65=0065	65=0065
66=0066	66=0066	66=0066	66=0066
67=0067	67=0067	67=0067	67=0067
68=0068	68=0068	68=0068	68=0068

CORE REQUIREMENTS FOR SRM32
COMMON 0 VARIABLES

RELATIVE STATE

0	VARIABLES	24	PROGRAM	226
---	-----------	----	---------	-----

END OF COMPILATION

11/25/68

*STORE WS UA SBW32
CART ID 0305 DB ADDR 5A59 DB CNT 0011

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// FOR
*ONE WORD INTEGERS

*LIST ALL

SUBROUTINE SBM30(GALFT,GARIT,SIGNL,DTAU,MIBP,NSBP,NX,XL,XK,REZ,
IGAZER)

C THIS SUBROUTINE CALCULATES THE
C IMPACTION EFFICIENCY OF A SPHERE
C

DIMENSION G(4),DG(4)

WRITE(3,200)

WRITE(3,201)GALFT,GARIT,SIGNL,DTAU,MIBP,NSBP,NX

C HALF INTERVAL ITERATION FOR INITIAL G4 VALUE
C

DO 31 ITER=1,NX

C SET AND PRINT INITIAL CONDITIONS
C

M=0

NSTEP=0

TAU=0.0

G(3)=XL

GAZER=(GALFT+GARIT)/2.0

G(4)=GAZER

CALL SBM34 (G,UX,UY,ITUBE)

G(1) = UX

G(2)=UY

RE=REZ*((UY-G(2))**2+(UX-G(1))**2)**0.5

XCDRE=CDRE(IRE)

IP=ITER/NIRP*NIRP

IF(IP-ITER)5,7,5

5 IF(ITER-1)6,7,6

6 IF(ITER-NX)8,7,8

7 CONTINUE

WRITE (3,205)

WRITE(3,203)ITER,GALFT,GAZER,GARIT,TAU,G(1),G(2),G(3),G(4),UX,UY,

1XCDRE

C CALL ON RUNGE KUTTA SUBROUTINE
C

8 CONTINUE

M=M+1

CALL SBM22(4,G,DG,TAU,DTAU,IRUNG,M)

IF(IRUNG-1)10,9,10

9 RE=REZ*((UY-G(2))**2+(UX-G(1))**2)**0.5

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XCDRE=CDRE(RE)
DG(1)=(XCDRE/(24.0* XK1))* (UX-G(1))
DG(2)=(XCDRE/(24.0* XK1))* (UY-G(2))
DG(3)=G(1)

DG(4)=G(2)

GO TO 8

10 CONTINUE

M=0

C CALCULATE FLUID VELOCITY AT PARTICLE POSITION

C CALL SBM34 (G,UX,UY,ITUBE)

C PRINT SOLUTIONS

C IS = ITER/MIBP-MIBP

IF(15-ITER)11,13,11

11 IF(ITER-1)12,13,12

12 IF(ITER-NX)16,13,16

13 NSTEP=NSTEP+1

IF(NSTEP-NSBP)16,14,16

14 CONTINUE

NSTEP=0

TAW = TAU+0.0001

WRITE(9,204)TAW,G(1),G(2),G(3),G(4),UX,UY,XCDRE

C INTEGRATE ACROSS ANOTHER STEP IF REQUIRED

C 16 CONTINUE

IF(G(4)-1.0)17,17,18

17 DELX=SQRT(1.0-G(4)**2)

GO TO 19

18 DELX=0.0

19 HITS=G(3)+G(1)*1.1*DTAU+DELX

IF(HITS)18,8,20

20 CONTINUE

C CHANGE INCREMENT SIZE NEAR SPHERE AND INTEGRATE FURTHER

C DTAW=DTAU/10.0

C CALL SBM32(G,TAU,DTAW,XK,REZ,UX,UY,XCDRE)

C PRINT SOLUTIONS

C IF(15-ITER)21,23,21

21 IF(ITER-1)22,23,22

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22 IF(ITER-NX)24,23,24
23 CONTINUE
WRITE(3,204)TAU,G(1),G(2),G(3),G(4),UX,UY,XCDRE
24 CONTINUE

DTAU=DTAU/100.0
CALL SBMS2(G,TAU,DTAU,XK,REZ,UX,UY,XCDRE)

PRINT SOLUTIONS

IF(15-ITER)25,27,25
25 IF(ITER-1)26,27,26
26 IF(ITER-NX)28,27,28
27 CONTINUE
WRITE(3,204)TAU,G(1),G(2),G(3),G(4),UX,UY,XCDRE
28 CONTINUE

C CALCULATE ORDINATE AT TANGENT POINT OF TANGENT PATH

C ORD = G(1)/SQRT(G(1)**2 + G(2)**2)

C FIND INTERVAL HALF WITH THE SIGN CHANGE

C IF((G(4)-ORD)*SIGNL-0.0)29,29,30

29 GART=GART

30 GALT=GALT

31 CONTINUE

EM = GART**2

WRITE(3,207) EM

C RETURN

C FORMATS FOR OUTPUT STATEMENTS

200 FORMAT(1H0,41X,3HIMPACTION EFFICIENCY OF A SPHERE /

1 1H0)

201 FORMAT(10HOGALEF = ,F10.6/10H GART = ,F10.6/10H SIGNL = ,

1 F3.0/10H DTAU = ,F10.6/10H NLRP = ,13/10H NSBP = ,13/

2 10H NX = ,13)

203 FORMAT(10HITER = ,13/10H GALEF = ,F10.6/10H GART = ,

1 F10.6/10H GART = ,F10.6/7H0 TAU,11X,4HG(1),12X,

2 4HG(2),12X,4HG(3),12X,4HG(4),14X,2HUX,14X,2HUY,

3 12X,4HCORE /

4 1H0,F7.4,4F16.6,3F16.4)

204 FORMAT(1H,F7.4,4F16.6,3F16.4)

205 FORMAT(40H1THE MOTION OF A CRITICAL PARTICLE IS GIVEN BY)

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207 FORMAT(30)THE IMPACTION EFFICIENCY IS (E10.4)

END

VARIABLE ALLOCATIONS

GIR J=0006-0000 DGR J=000E-0008 TAU(R J=0010 UK(R J=0012 UY(R J=0014 REIR J=0016
XCDREIR J=0018 TAU(R J=001A DELX(R J=001C MITS(R J=001E DTAM(R J=0020 ORD(R J=0022
FM(R J=0024 ITER(I J=002A M(I J=002B NSTEP(I J=002C ITURE(I J=002D IP(I J=002E
IRUNG(I J=002F IS(I J=0030

STATEMENT ALLOCATIONS

200 -004D 201 -0046 203 -009E 204 -00E6 205 -00EE 207 -0107 5 -01CE 6 -01D4 7 -01DA 8 -0202
9 -0217 10 -026D 11 -0287 12 -028D 13 -028D 14 -029F 16 -02C5 17 -02CE 18 -02DF 19 -02E3
20 -02F8 21 -030E 22 -0314 23 -031A 24 -0336 25 -034C 26 -0352 27 -0358 28 -0374 29 -039C
30 -03A2 31 -03A6

FEATURES SUPPORTED
ONE WORD INTEGERS

CALLD SUBPROGRAMS

SRM3A CDRE SRM22 FSDRT SBM32 FAXB FADD SCOMP STOFX FSUBX FMPY FLDX FSTO
FS-0X FSR FSVR FSVR FAXI FAXI SWRT

REAL CONSTANTS

.000000E 00=0036 -200000E 01=0038 .500000E 00=003A .100000E 02=003C .100000E 03=0040
.110000E 01=0042 .100000E 02=0044 .100000E 03=0046

INTEGER CONSTANTS

3=004B 1=0049 0=004A 2=004B 4=004C

CORE REQUIREMENTS FOR SRM30

COMMON 0 VARIABLES 54 PROGRAM 904

RELATIVE ENTRY POINT ADDRESS IS 0119 (HEX)

END OF COMPILATION

// DUP

*STORE WS UA SRM30

CART ID 0305 DR ADDR 5AGA DR CNT 003E

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// FOR
*ONE WORD INTEGERS
*LIST ALL
SUBROUTINE SPM31(XL,GAZER,DTAU,XK,REZ,PX,NZER,NJBP)
C
C THIS SUBROUTINE CALCULATES THE MOTION OF PARTICLES
C IN A FLUID STREAM MOVING TOWARD A SPHERE
C AND CALCULATES THE FORCE OF PARTICLE IMPACT ON THE SPHERE
C
C DIMENSION G(4),DG(4)
C DIMENSION YZER(500)
C SET NUMBER OF INCREMENTS AT INITIAL POSITION
C
C WRITE(3,200)
C WRITE(3,201)NZER,NJBP
C WRITE(3,202)
C NCE=NZER+1
C DELY=GAZER/FLOAT(NZER)
C FSUM=0.0
C STEPWISE INTEGRATION FOLLOWING PARTICLE POSITION
C
C DO 30 ITER=1,NCE
C SET AND PRINT INITIAL CONDITIONS
C
C M=0
C TAU=0.0
C G(3)=XL
C YZER(ITER)=FLOAT(ITER-1)*DELY
C GAZER=YZER(ITER)
C G(4)=GAZER
C CALL SPM34 (G,UX,UY,ITURE)
C UXZER=UX
C G(1)=UX
C G(2)=UY
C CALL ON RUNGE KUTTA SUBROUTINE
C
C B CONTINUE
C M=M+1
C CALL SPM22(4,G,DG,DTAU,IRUNG,M)
C IF(IRUNG-1)10,9,10
C 9 RE=REZ+((UY-G(2))*2+(UX-G(1))*2)*0.5
C XCORE=CDRE(RE)

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PAGE 16

DG(1)=(XCDRE/(24.0*WK))*(UX-G(1))
DG(2)=(XCDRE/(24.0*WK))*(UY-G(2))
DG(3)=G(1)
DG(4)=G(2)

GO TO 8

10 CONTINUE

M=0

C CALCULATE FLUID VELOCITY AT PARTICLE POSITION

C CALL SBM34 (G,UX,UY,ITUBE)

C INTEGRATE ACROSS ANOTHER STEP IF REQUIRED

IF(IG(4) - 1.0)11,11,12

11 DELX = SORT(1.0 - G(4)**2)

GO TO 13

12 DELX = 0.0

13 WITS=G(3)+G(1)*1.1*DTAU+DELX

IF(WITS)8,8,18

18 CONTINUE

C CHANGE INCREMENT SIZE NEAR SPHERE AND INTEGRATE FURTHER

DTAU=DTAU/10.0

CALL SBM32(G,TAU,DTAU,XK,REZ,UX,UY,XCDRE)

DTAU=DTAU/100.0

CALL SBM32(G,TAU,DTAU,XK,REZ,UX,UY,XCDRE)

C CO-ORDINATES, VELOCITY, AND PRESSURE DERIVATIVE AT SPHERE

VX=G(1)

VY=G(2)

X=G(3)

Y=G(4)

V=V(SORT(VX**2+VY**2))

PI = 3.14159265358979323846264

GAMMA = PI - 2.0*ATAN(Y/SORT(1.0-Y**2)) - ATAN(VY/VX)

FY= UXZER+VX- V*COS(GAMMA)

FSUM = FSUM + FLOAT(2*ITER-1)*FY

CONTINUE

C PRINT SOLUTIONS

IS = ITER/NJRP+NJBP

IF(15-ITER)21,23,21

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INTEGER CONSTANTS

3=0442 1=0443 0=0444 4=0445 2=0446

CORE REQUIREMENTS FOR SAM31

COMMON 0 VARIABLES 1072 PROGRAM 688

RELATIVE ENTRY POINT ADDRESS IS 04CC (HEX)

END OF COMPILATION

// DUP

*STORE VS UA SBM31

CART ID 0305 DB ADDR 5AAB DB CNT 0030

// EJECT

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// FOR
*ONE WORD INTEGERS
*IOCS(CARD)
*IOCS(1132 PRINTER)
*LIST ALL

C ESTABLISH PARAMETERS FOR STEP BY STEP INTEGRATION AND HALF
C INTERVAL METHOD
C GALFT AND GARIT ARE LOWER AND UPPER BOUNDS RESPECTIVELY FOR
C STARTING LOCATION OF PARTICLE
C SIGNAL IS SIGN CORRECTION FOR HALF INTERVAL METHOD
C IN THIS PROBLEM IT IS -1.0
C DTAU IS THE TIME INCREMENT FOR STEP BY STEP INTEGRATION
C NIRP IS INTERVAL OF WRITTEN PARTICLE PATHS
C NSRP IS INTERVAL OF WRITTEN INTEGRATION STEPS
C NX IS NUMBER OF ITERATIONS USED TO DETERMINE PARTICLE STARTING
C POINT

C ESTABLISH WHETHER A TUBE IS PRESENT
C
C IF ITURE IS POSITIVE A TUBE IS PRESENT
C IF ITURE IS ZERO OR NEGATIVE SPHERE IS IN FREE SPACE

1 READ(2,100)GALFT,GARIT,SIGML,DTAU,NIRP,NSRP,NX,ITUBE

C ESTABLISH PHYSICAL PROPERTIES FOR CALCULATING IMPACTION EFFICIENCY

C DC IS SPHERE DIAMETER, CM
C DP IS PARTICLE DIAMETER, CM
C RHO IS FLUID DENSITY, GM/CC
C SIGMA IS PARTICLE DENSITY, GM/CC
C XMU IS ABSOLUTE VISCOSITY OF FLUID, POISE
C UF IS FREE STREAM VELOCITY, CM/SEC

C READ(2,101)DC,DP,RHO,SIGMA,XMU,UF

C XL IS UPSTREAM STARTING POSITION FOR CALCULATING PARTICLE MOTION

C READ(2,102)XL
C REFZ=RHO*DP*UF/XMU

XR=SIGMA*DP**2*UF/19.*XMU*DC)

P = 9.*RHO**2*UF*DC/(XMU*SIGMA)

WRITE(3,200)

WRITE(3,201)

C XK IS INERTIAL PARAMETER CALLED STOKES NUMBER

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C REZ IS FREE STREAM REYNOLDS NUMBER OF SPHERICAL PARTICLE
C P IS DIMENSIONLESS GROUP INDEPENDENT OF DROP SIZE
C

WRITE(3,202)XL,REZ,XK,P,DC,DP,RHO,SIGMA,XMU,UF,ITUBE

C CALCULATE STARTING POSITION OF TANGENT PARTICLE

C CALL SBM30(GALFT,GARIT,SIGNL,DTAU,NIBP,NSBP,NX,XL,XK,REZ,G4ZER)

C ESTABLISH NUMBER OF INCREMENTS FOR INTEGRATING PARTICLE FORCE

C NZER IS NUMBER OF INCREMENTS

C NJBP IS INTERVAL OF WRITTEN INCREMENTS

READ(2,103)NZER,NJBP

C CALCULATE FORCE PRODUCED BY PARTICLES

C CALL SBM31(XL,G4ZER,DTAU,XK,REZ,PK,NZER,NJBP)

RECYL=RHO*DC*UF/XMU

CDAIR = CDRE(RECYL)/RECYL

C OUTPUT RESULTS

C WRITE(3,204)RECYL

IF(RECYL - 10000)10,11,11

10 CONTINUE

WRITE(3,206)CDAIR

11 CONTINUE

READ(2,111)NSTOP

IF(NSTOP)1,30,30

30 CALL EXIT

C FORMATS FOR INPUT AND OUTPUT STATEMENTS

C 100 FORMAT(10X,F10.7,20X,F10.7,19X,F3.0/ 10X,F10.7,20X,I3,27X,I2/

1 10X,I2,10X,I2)

101 FORMAT(F10.5,F10.7,F10.6, F10.6,F10.7,F10.1)

102 FORMAT (F10.7)

103 FORMAT(I5,I5)

111 FORMAT(I5)

200 FORMAT(1H1, 35X, 49HTHE DRAG ON SPHERES IN A STREAM OF DUST-LADEN

1 AIR / 1H0)

201 FORMAT(28H0THE PHYSICAL PARAMETERS ARE)

202 FORMAT(10H0XL = ,F10.7/10H REZ = ,E12.6/10H XK = ,

1 E12.6/10H P = ,E12.6/

PAGE 21

2 10H0DC = , F10.5/10H DP = , F10.7/10H RMO = , F10.6/
 3 10H SIGMA = , F10.6/10H XMU = , F10.7/10H UF = , F10.1/
 4 10H ITURE = , 13)

204 FORMAT(32H0THE TARGET REYNOLDS NUMBER IS ,E10.4)

206 FORMAT(59H0THE DRAG COEFFICIENT OF THE SPHERE DUE TO THE AIR ALON

1E IS,F9.4)

END

VARIABLE ALLOCATIONS

G4LFT(R)=C000	G4RIT(P)=C002	SIGNLR)=C004	DTAUR)=C006	DCIR)=C008	DRIR)=C00A
PHOIR)=C00C	SIGNA(R)=C00E	XMU(R)=C010	UF(R)=C012	XLIR)=C014	REZIR)=C016
XK(R)=C018	P(R)=C01A	G4ZER(R)=C01C	PRIR)=C01E	RECYL(R)=C020	CDAIR(R)=C022
NIRP(I)=C026	MSBP(I)=C027	NX(I)=C028	ITUBE(I)=C029	NZER(I)=C02A	NJBPI(I)=C02B
NSTOP(I)=C02C					

STATEMENT ALLOCATIONS

100	=C013	101	=C046	102	=C04D	103	=C04F	111	=C052	200	=C054	201	=C075	202	=C085	204	=C0DD	206	=C0FE
1	=C018	10	=C01E	11	=C01E	30	=C01F												

FEATURES SUPPORTED
 ONE WORD INTEGERS
 IOCS

CALLED SURPROGRAMS

SRM30	SRM31	CDRE	FMPY	FDIV	FLD	FSTO	FSBR	FDVR	FAXI	FLOAT	CARDZ	PRNTZ	SRED	SMRT
SCOMP	SFIO	SIOF	STOI											

REAL CONSTANTS

.900000E 01=C00E

INTEGER CONSTANTS

2=C01C 3=C031 10000=C032

CORE REQUIREMENTS FOR

COMMON 0 VARIABLES 46 PROGRAM 450

END OF COMPILATION

// XEO

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THE DRAG ON SPHERES IN A STREAM OF DUST-LADEN AIR

THE PHYSICAL PARAMETERS ARE

XL = -5.0000009
REZ = 0.735665E 02
XK = 0.339462E 03
P = 0.159429E 02
DC = 0.800000
DP = 0.0155000
RHO = 0.001213
SIGMA = 2.600000
XMO = 0.0001789
UF = 700.0
ITURE = 1

IMPACTION EFFICIENCY OF A SPHERE

GALEF = 0.000000
GARIT = 1.000000
SIGNL = -1.
OTAU = 0.100000
NIRP = 10
NSHP = 2
NX = 20

THE MOTION OF A CRITICAL PARTICLE IS GIVEN BY

ITER = 1
G4LEF = 0.000000
G47ER = 0.500000
G49IT = 1.000000

TAU	G(1)	G(2)	G(3)	G(4)	UX	UY	CDRE
0.0000	0.992235	0.001170	-5.000000	0.500000	0.9922	0.0011	24.0000
0.2000	0.992235	0.001170	-4.801552	0.500234	0.9912	0.0013	24.1144
0.4000	0.992234	0.001170	-4.603104	0.500468	0.9901	0.0016	24.3144
0.6000	0.992232	0.001171	-4.404656	0.500702	0.9887	0.0019	24.6838
0.8000	0.992230	0.001171	-4.206209	0.500936	0.9871	0.0023	25.0545
1.0000	0.992226	0.001172	-4.007762	0.501170	0.9851	0.0028	25.5006
1.2000	0.992221	0.001173	-3.809317	0.501405	0.9828	0.0034	26.0393
1.4000	0.992215	0.001175	-3.610873	0.501639	0.9799	0.0042	26.6888
1.6000	0.992206	0.001177	-3.412430	0.501874	0.9764	0.0052	27.4637
1.8000	0.992194	0.001180	-3.213989	0.502110	0.9719	0.0066	28.3636
2.0000	0.992179	0.001184	-3.015552	0.502346	0.9664	0.0085	29.3535
2.2000	0.992158	0.001190	-2.817118	0.502584	0.9592	0.0110	30.3524
2.4000	0.992131	0.001198	-2.618688	0.502822	0.9500	0.0146	31.3039
2.6000	0.992096	0.001210	-2.420265	0.503063	0.9379	0.0197	32.5793
2.8000	0.992046	0.001227	-2.221849	0.503307	0.9216	0.0273	35.1527
3.0000	0.991977	0.001253	-2.023447	0.503555	0.8993	0.0387	37.8687
3.2000	0.991878	0.001294	-1.825060	0.503809	0.8683	0.0566	41.2151
3.4000	0.991733	0.001361	-1.626698	0.504074	0.8241	0.0858	45.4350
3.6000	0.991511	0.001477	-1.428372	0.504357	0.7601	0.1354	50.8992
3.8000	0.991162	0.001689	-1.230102	0.504672	0.6665	0.2240	58.1905
4.0000	0.990588	0.002105	-1.031924	0.505048	0.5317	0.3305	68.2592
4.1599	0.989818	0.002824	-0.873486	0.505434	0.4024	0.6495	87.4018
4.1699	0.989753	0.002896	-0.863587	0.505462	0.3930	0.6701	89.2955

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THE MOTION OF A CRITICAL PARTICLE IS GIVEN BY

ITER = 10
GALEF = 0.986328
GAZER = 0.987304
GARIT = 0.988281

TAU	G(1)	G(2)	G(3)	G(4)	UX	UY	CDRE
0.0000	0.992871	0.002153	-5.000000	0.987304	0.9928	0.0021	24.0000
0.2000	0.992871	0.002153	-4.601424	0.987735	0.9920	0.0025	24.1050
0.4000	0.992870	0.002153	-4.602849	0.988165	0.9910	0.0029	24.2421
0.6000	0.992869	0.002154	-4.404275	0.988596	0.9899	0.0034	24.6219
0.8000	0.992866	0.002155	-4.205701	0.989027	0.9885	0.0041	24.9539
1.0000	0.992863	0.002156	-4.007127	0.989458	0.9870	0.0049	25.3495
1.2000	0.992859	0.002158	-3.808554	0.989889	0.9851	0.0059	25.8227
1.4000	0.992854	0.002161	-3.609982	0.990321	0.9829	0.0072	26.3884
1.6000	0.992847	0.002164	-3.411412	0.990754	0.9802	0.0089	27.0605
1.8000	0.992838	0.002169	-3.212843	0.991187	0.9771	0.0111	27.8458
2.0000	0.992826	0.002176	-3.014276	0.991622	0.9732	0.0139	28.7317
2.2000	0.992811	0.002185	-2.815712	0.992058	0.9686	0.0176	29.6714
2.4000	0.992792	0.002198	-2.617151	0.992496	0.9629	0.0226	30.5895
2.6000	0.992767	0.002214	-2.418595	0.992937	0.9561	0.0294	31.4721
2.8000	0.992737	0.002238	-2.220044	0.993382	0.9478	0.0388	32.3664
3.0000	0.992696	0.002272	-2.021500	0.993833	0.9380	0.0519	35.1330
3.2000	0.992644	0.002320	-1.822965	0.994292	0.9267	0.0704	37.5175
3.4000	0.992577	0.002392	-1.624443	0.994763	0.9145	0.0966	40.3086
3.6000	0.992492	0.002500	-1.425935	0.995252	0.9032	0.1338	43.5836
3.8000	0.992388	0.002664	-1.227447	0.995767	0.8975	0.1858	47.4096
4.0000	0.992271	0.002912	-1.028981	0.996324	0.9066	0.2551	51.8058
4.2000	0.992165	0.003283	-0.830537	0.996941	0.9475	0.3376	56.6614
4.4000	0.992129	0.003809	-0.632109	0.997649	1.0426	0.4116	61.6017
4.6000	0.992268	0.004474	-0.433672	0.998476	1.2030	0.4248	65.8702
4.8000	0.992700	0.005142	-0.235180	0.999439	1.3892	0.3089	68.5349
5.0000	0.993434	0.005561	-0.036569	1.000514	1.4962	0.0545	69.3931
5.0299	0.993572	0.005570	-0.006764	1.000681	1.5277	0.0103	71.6809
5.0359	0.993600	0.005571	-0.000803	1.000714	1.5378	0.0012	71.6874

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ITER = 2C
G4LEF = 0.986612
G4ZFR = 0.986613
G4RIT = 0.986614

TAU	G(1)	G(2)	G(3)	G(4)	UX	UY	CDRE
0.0000	0.992870	0.002152	-5.000000	0.986613	0.9928	0.0021	24.0000
0.2000	0.992869	0.002152	-4.801426	0.987043	0.9920	0.0025	24.1050
0.4000	0.992869	0.002152	-4.602852	0.987474	0.9910	0.0029	24.3421
0.6000	0.992867	0.002153	-4.404278	0.987904	0.9899	0.0034	24.6220
0.8000	0.992865	0.002154	-4.205704	0.988335	0.9885	0.0041	24.9540
1.0000	0.992862	0.002155	-4.007130	0.988765	0.9870	0.0049	25.3498
1.2000	0.992858	0.002157	-3.808557	0.989197	0.9851	0.0059	25.8231
1.4000	0.992853	0.002159	-3.609985	0.989628	0.9829	0.0072	26.3889
1.6000	0.992845	0.002163	-3.411415	0.990061	0.9802	0.0089	27.0612
1.8000	0.992836	0.002168	-3.212846	0.990494	0.9771	0.0111	27.8467
2.0000	0.992825	0.002175	-3.014279	0.990928	0.9732	0.0139	28.7328
2.2000	0.992810	0.002184	-2.815715	0.991364	0.9686	0.0176	29.6726
2.4000	0.992790	0.002196	-2.617155	0.991802	0.9629	0.0226	30.5908
2.6000	0.992766	0.002213	-2.418598	0.992243	0.9561	0.0294	31.4736
2.8000	0.992735	0.002237	-2.220047	0.992687	0.9478	0.0388	32.4702
3.0000	0.992695	0.002270	-2.021504	0.993138	0.9380	0.0519	35.1374
3.2000	0.992643	0.002319	-1.822969	0.993597	0.9266	0.0704	37.5233
3.4000	0.992575	0.002391	-1.624447	0.994067	0.9143	0.0966	40.3164
3.6000	0.992490	0.002499	-1.425940	0.994556	0.9031	0.1339	43.5941
3.8000	0.992386	0.002663	-1.227452	0.995071	0.8973	0.1859	47.4243
4.0000	0.992268	0.002912	-1.028986	0.995627	0.9064	0.2553	51.8262
4.2000	0.992162	0.003283	-0.830543	0.996245	0.9472	0.3381	56.6896
4.4000	0.992125	0.003810	-0.632116	0.996952	1.0424	0.4123	61.6398
4.6000	0.992264	0.004476	-0.433679	0.997780	1.2031	0.4258	65.9190
4.8000	0.992697	0.005147	-0.235187	0.998744	1.3899	0.3098	68.5916
5.0000	0.993539	0.005525	-0.026640	0.999873	1.5374	0.0409	71.7265
5.0280	0.993629	0.005529	-0.007762	0.999977	1.5388	0.0119	71.7420

THE IMPACTION EFFICIENCY IS 0.9734E 00

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WZER = 120

NJRP = 4

TAU	VX	VY	X	Y	UX	UY	FY
3.9319	1.014362	0.000000	-1.001004	0.000000	0.0019	0.0000	2.06391
3.9329	1.014354	0.000144	-0.999986	0.024930	0.0006	0.0383	2.06261
3.9339	1.014364	0.000338	-0.998960	0.058170	0.0060	0.0892	2.05690
3.9359	1.014378	0.000531	-0.996900	0.091410	0.0149	0.1395	2.04662
3.9399	1.014386	0.000726	-0.992805	0.124651	0.0245	0.1900	2.03174
3.9449	1.014403	0.000922	-0.987683	0.157893	0.0378	0.2399	2.01229
3.9499	1.014435	0.001117	-0.982546	0.191134	0.0577	0.2878	1.98830
3.9569	1.014465	0.001314	-0.975374	0.224377	0.0786	0.3356	1.95971
3.9649	1.014502	0.001512	-0.967173	0.257621	0.1033	0.3820	1.92655
3.9749	1.014538	0.001714	-0.956930	0.290867	0.1295	0.4283	1.88880
3.9849	1.014594	0.001912	-0.944678	0.324113	0.1620	0.4710	1.84651
3.9969	1.014649	0.002114	-0.934380	0.357362	0.1963	0.5132	1.79862
4.0109	1.014813	0.002230	-0.920041	0.390612	0.2329	0.5547	1.74840
4.0239	1.014887	0.002425	-0.906702	0.423860	0.2770	0.5992	1.69238
4.0399	1.014956	0.002631	-0.890306	0.457115	0.3218	0.6242	1.63175
4.0579	1.015036	0.002838	-0.871872	0.490374	0.3695	0.6574	1.56653
4.0769	1.015130	0.003041	-0.852407	0.523634	0.4214	0.6860	1.49676
4.0979	1.015234	0.003245	-0.830898	0.556900	0.4766	0.7117	1.42239
4.1209	1.015395	0.003351	-0.807344	0.590168	0.5352	0.7336	1.34361
4.1449	1.015517	0.003554	-0.782760	0.623440	0.5974	0.7489	1.26008
4.1719	1.015653	0.003759	-0.755115	0.656722	0.6628	0.7609	1.17195
4.2019	1.015804	0.003964	-0.724405	0.690015	0.7318	0.7681	1.07922
4.2349	1.015970	0.004086	-0.690833	0.723312	0.8045	0.7690	0.98198
4.2699	1.016153	0.004285	-0.654810	0.756620	0.8796	0.7606	0.88008
4.3109	1.016330	0.004425	-0.612877	0.789930	0.9601	0.7463	0.77356
4.3549	1.016556	0.004625	-0.567873	0.823292	1.0424	0.7195	0.66241
4.4049	1.016812	0.004815	-0.516742	0.856660	1.1279	0.6802	0.54663
4.4639	1.017063	0.004970	-0.456439	0.890066	1.2180	0.6248	0.42618
4.5349	1.017361	0.005144	-0.383902	0.923532	1.3118	0.5456	0.30099
4.6269	1.017753	0.005334	-0.289958	0.957102	1.4093	0.4272	0.17098
4.7789	1.018412	0.005533	-0.134866	0.990992	1.5107	0.2057	0.03570
4.8979	1.018916	0.005627	-0.013958	0.999916	1.5386	0.0208	0.00019

THE DRAG COEFFICIENT OF THE SPHERE DUE TO THE REFLECTION OF PARTICLES IS 2.0356

THE TARGET REYNOLDS NUMBER IS 0.3796E 04

THE DRAG COEFFICIENT OF THE SPHERE DUE TO THE AIR ALONE IS 0.3909
// PAUS

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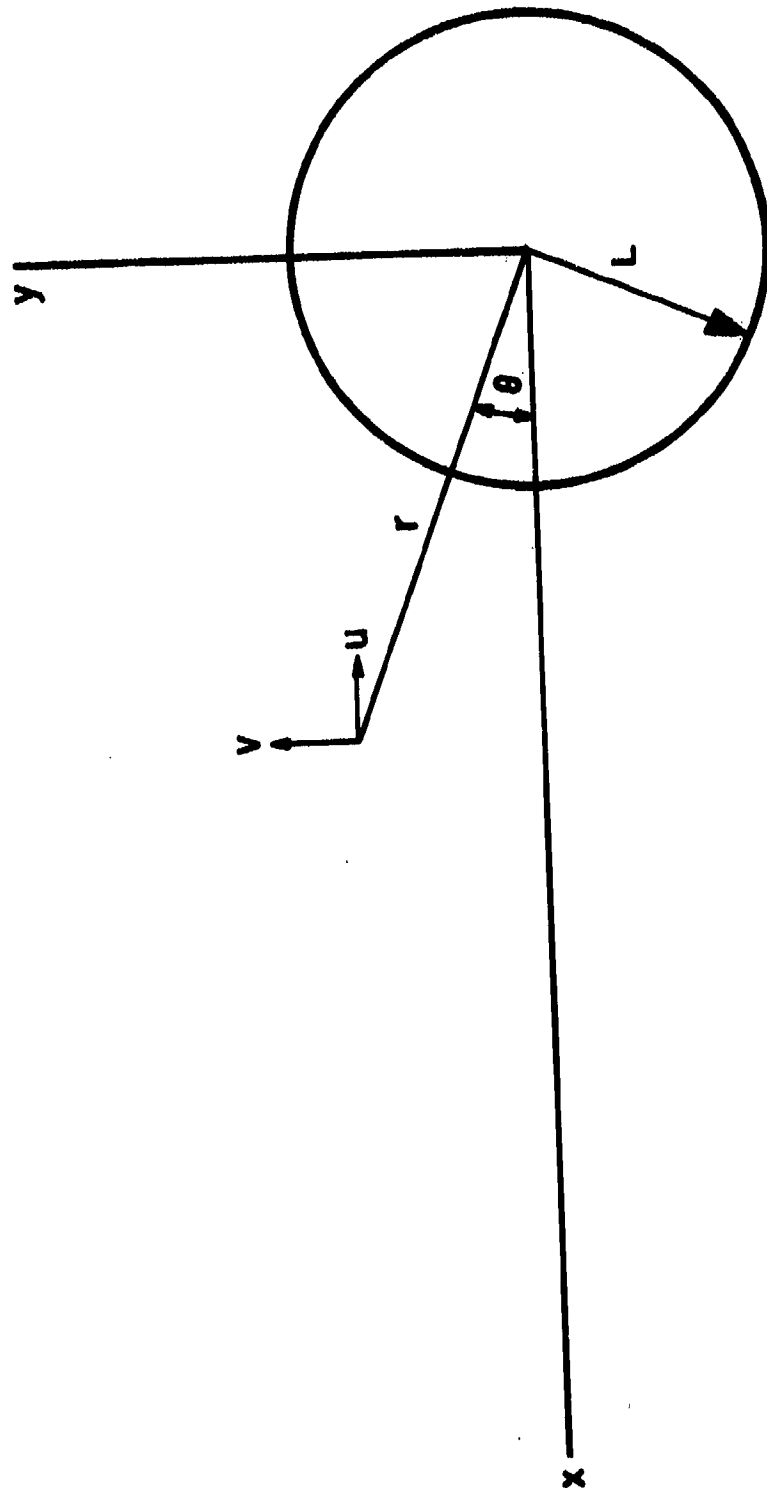


Fig. 1: Co-ordinate System for Transverse Flow with respect to a Circular Cylinder.

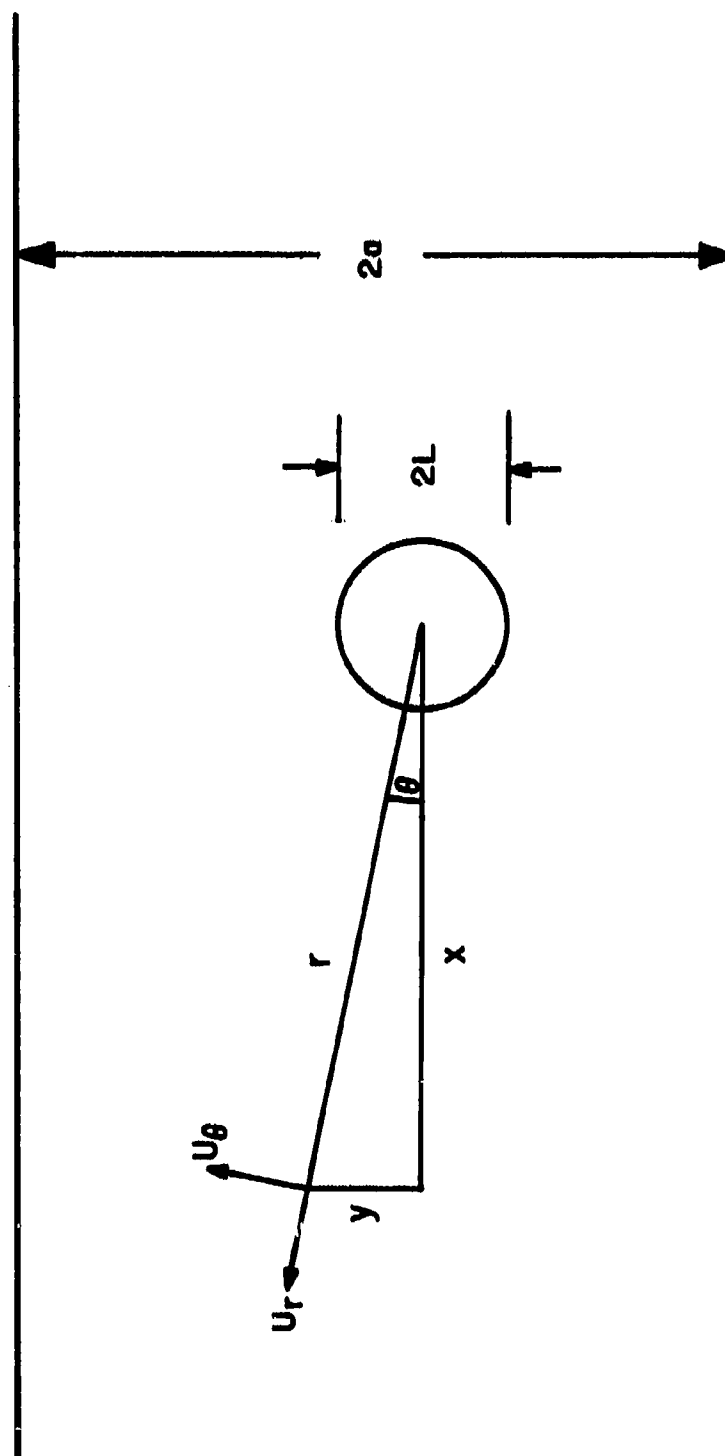


Fig. 2: Co-ordinate System for Flow around a Sphere in a Circular Cylinder.

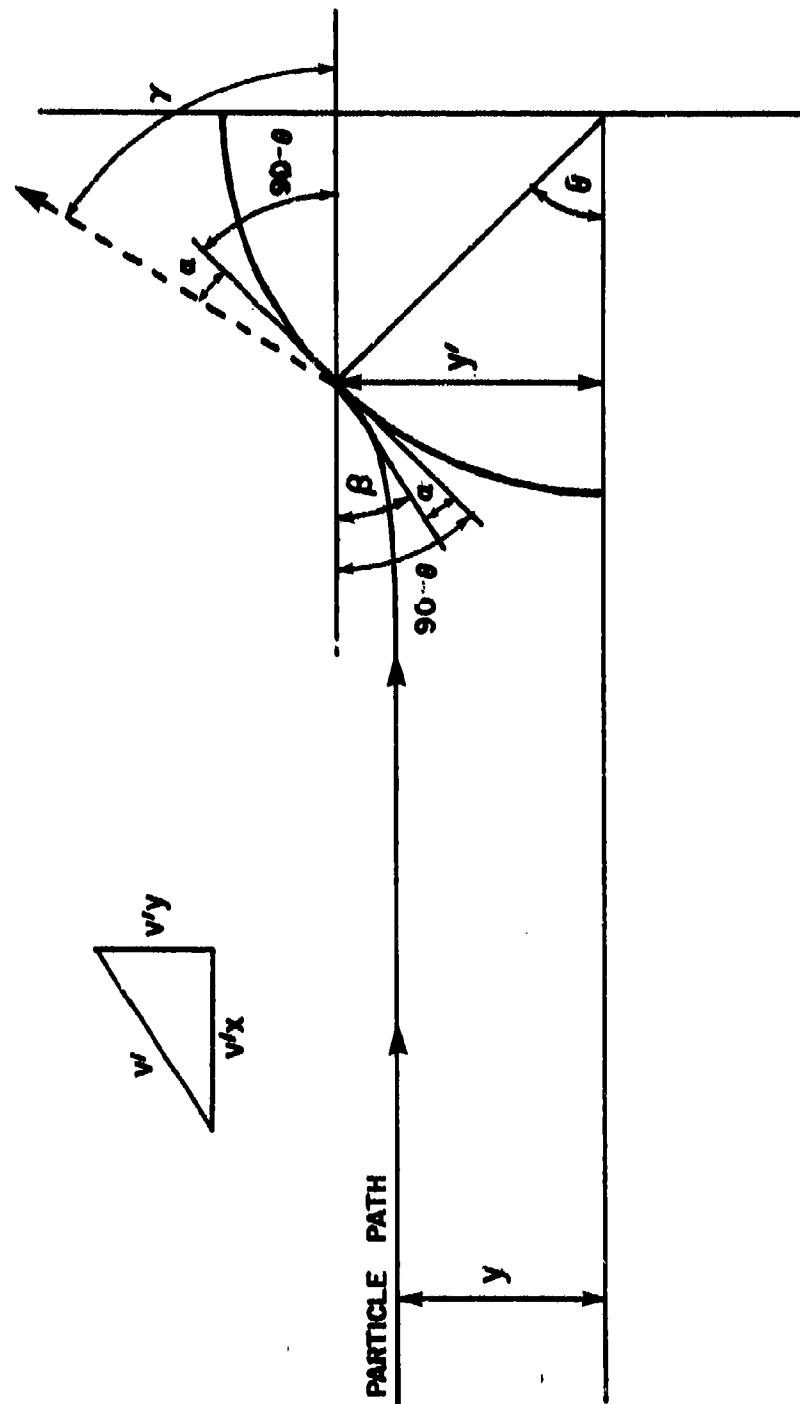


Fig. 3: Velocity Change of a Particle due to Interaction with a Sphere or Cylinder.

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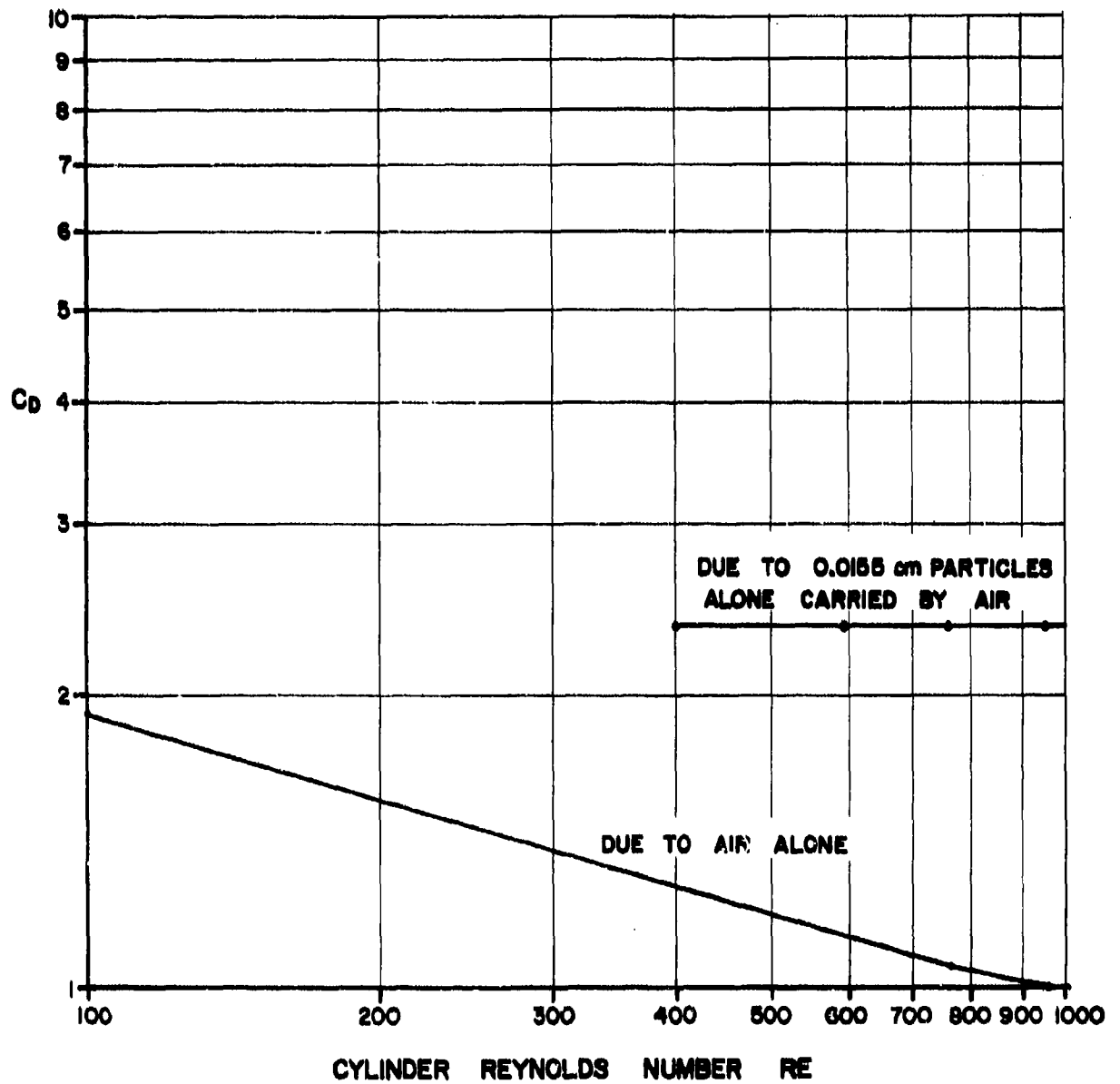


Fig. 4: Variation of Drag Coefficient for Cylinders.

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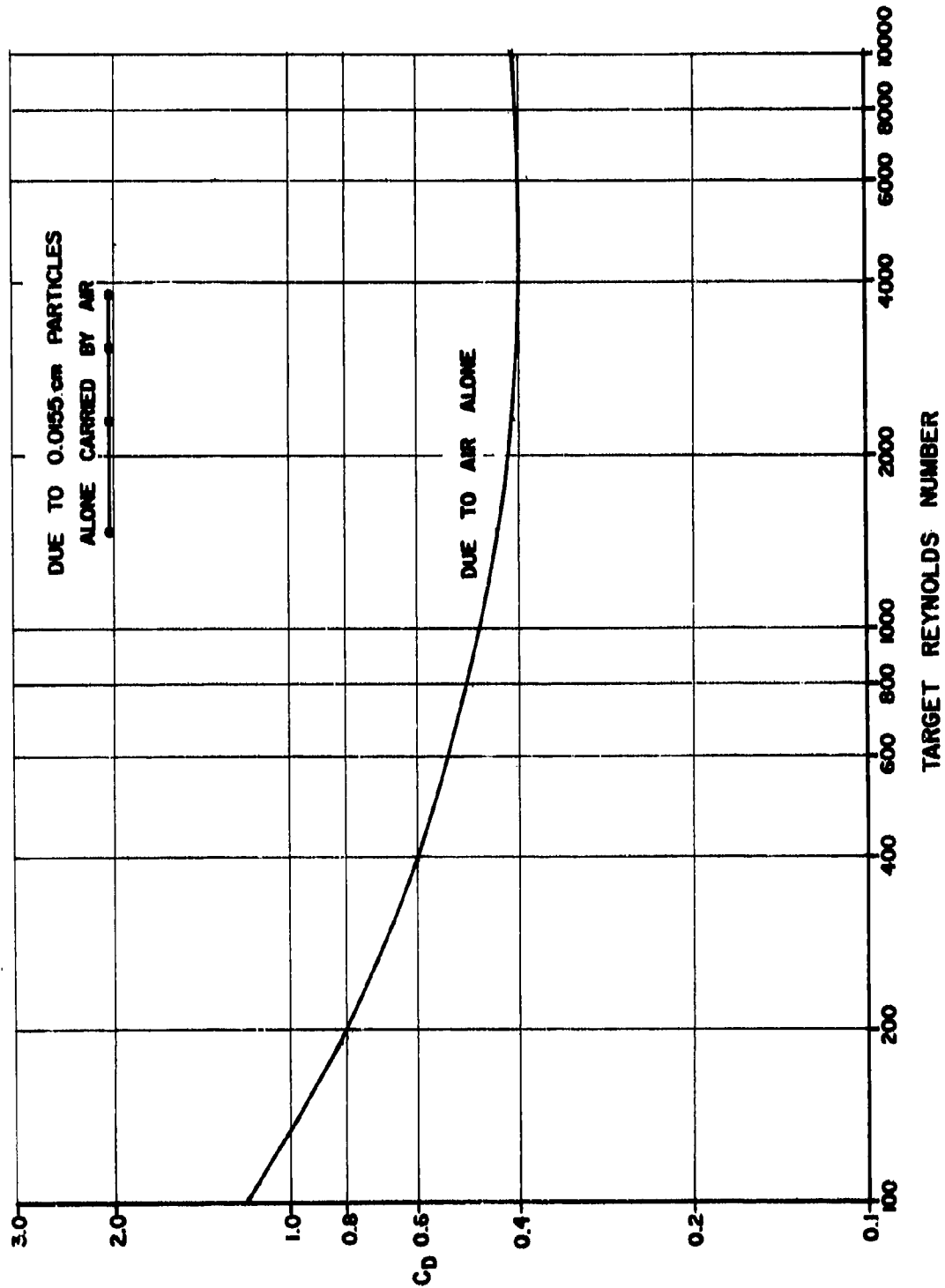


Fig. 5: Variation of Drag Coefficient for a Spherical Target.

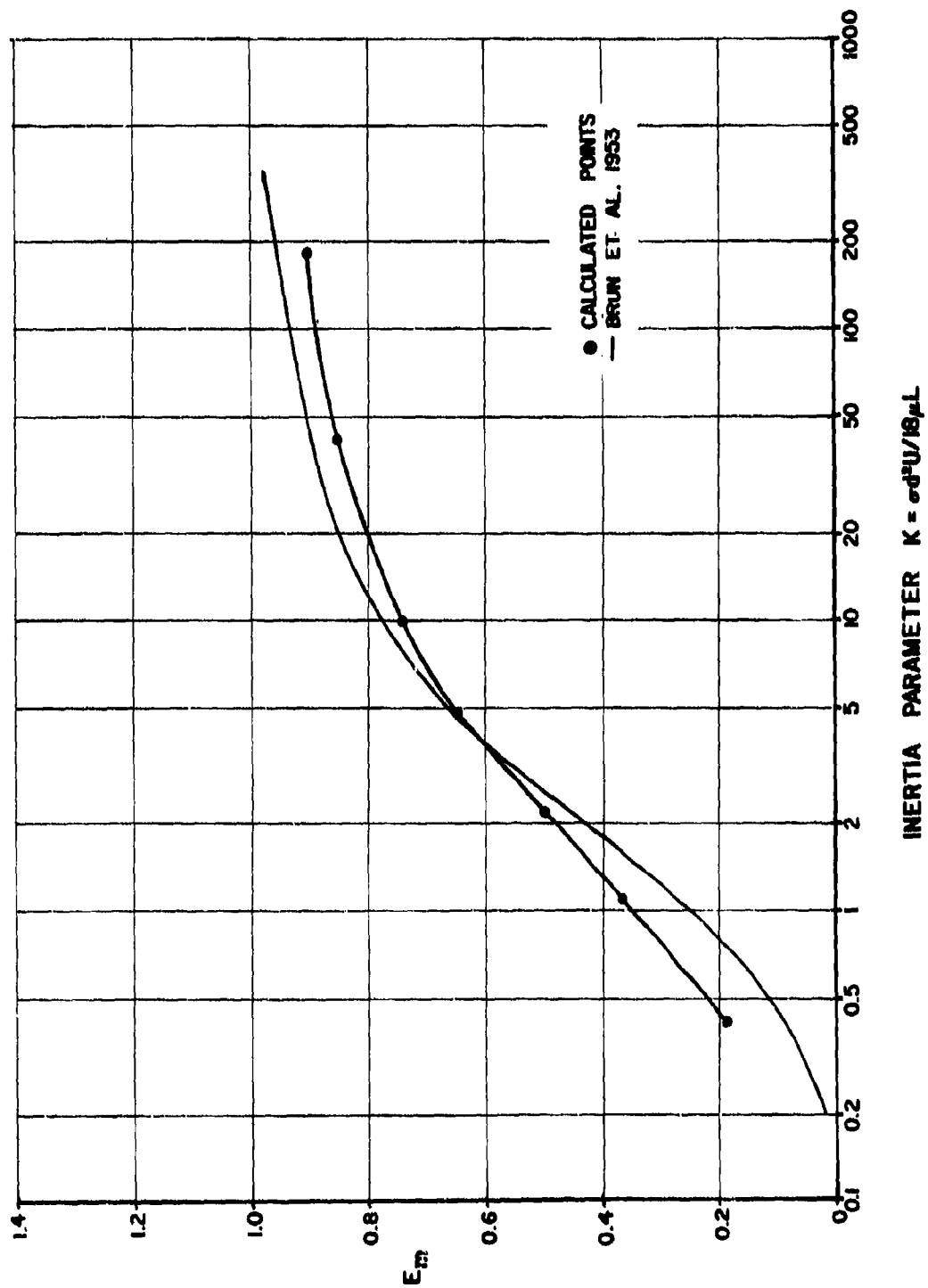


Fig. 6: Impact Efficiency for Cylinders, $\phi = 1000$.

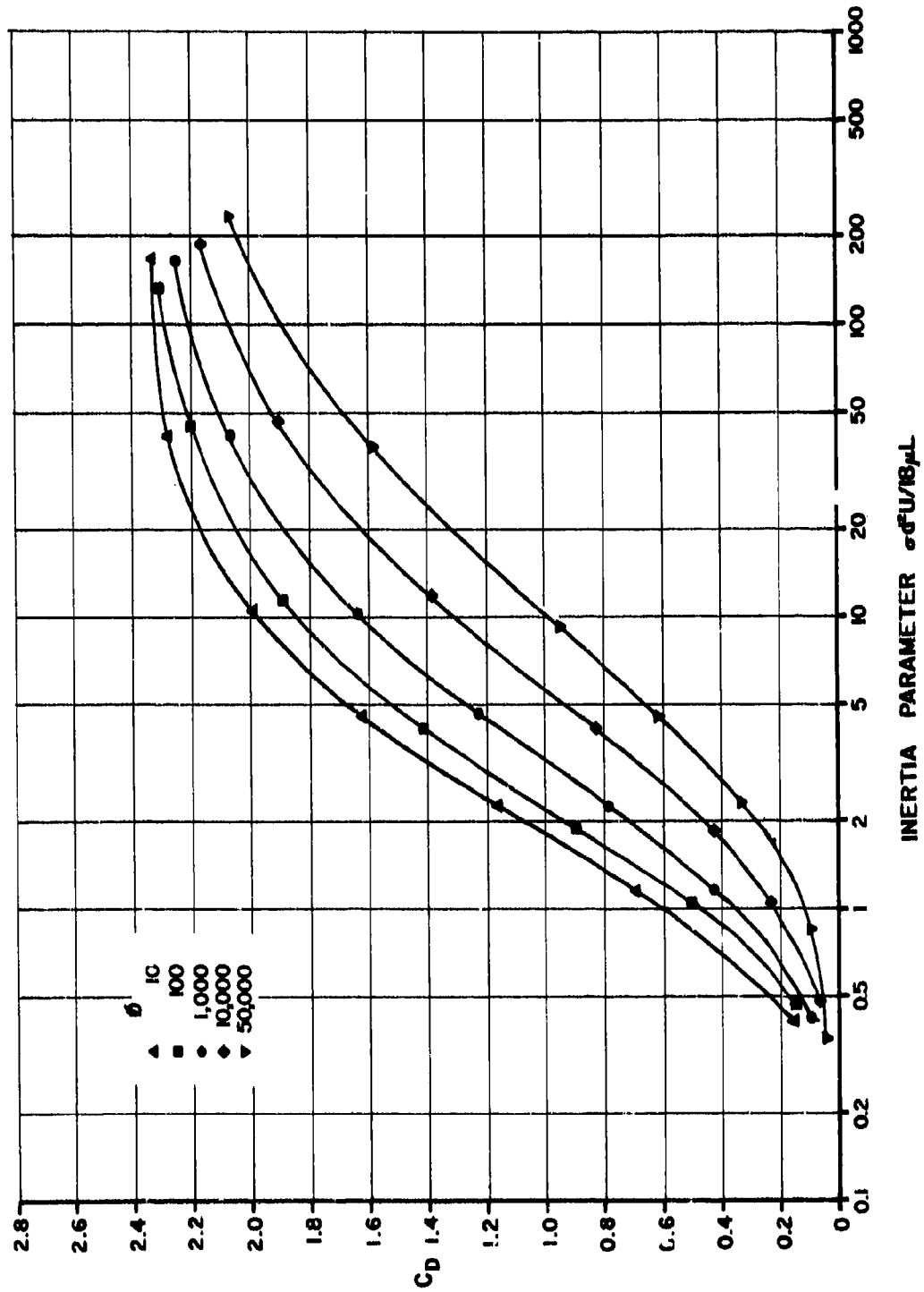


Fig. 7: Calculated Drag Coefficient for Cylinders due to Particles alone in an Inviscid Flow.

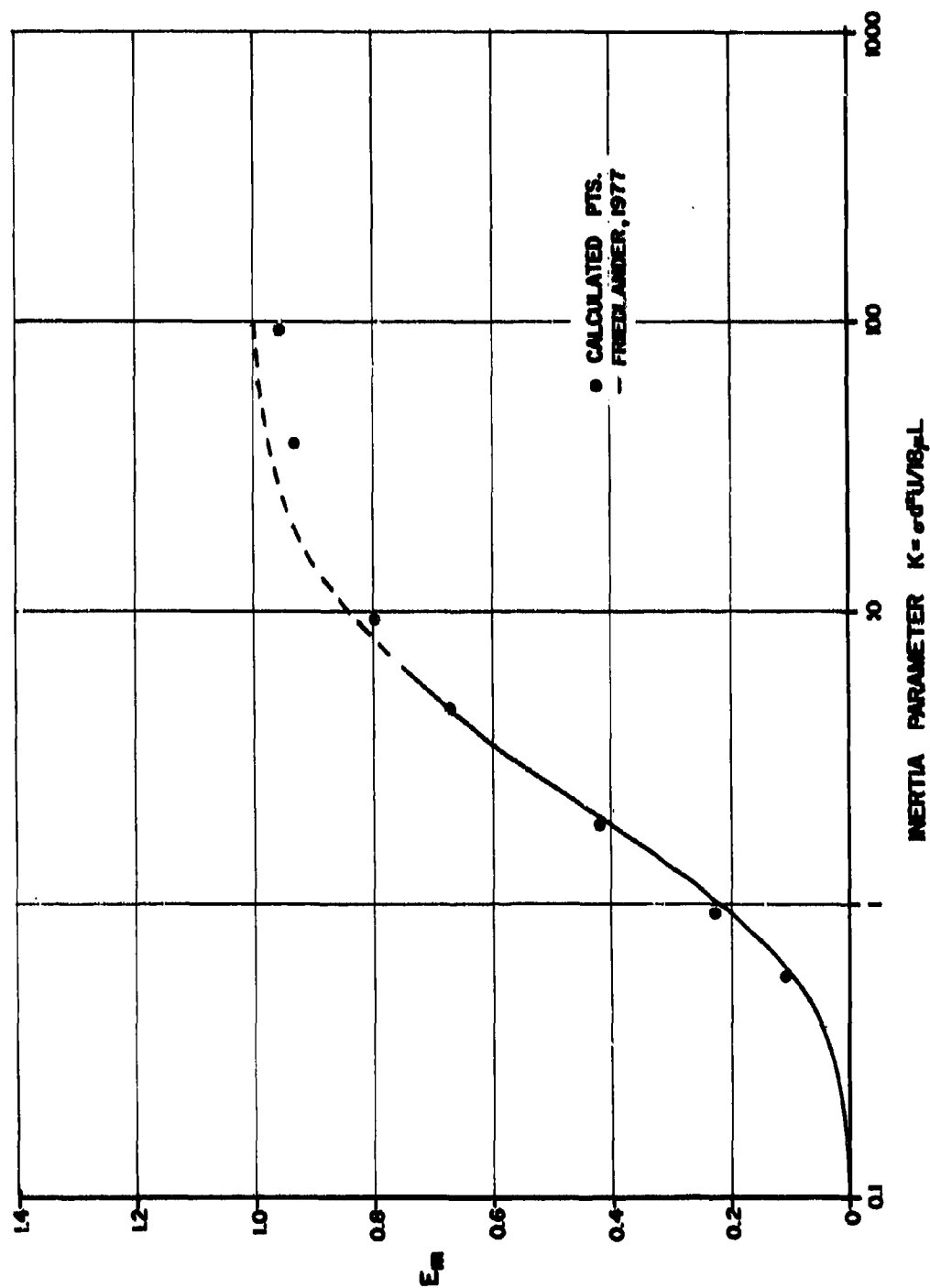
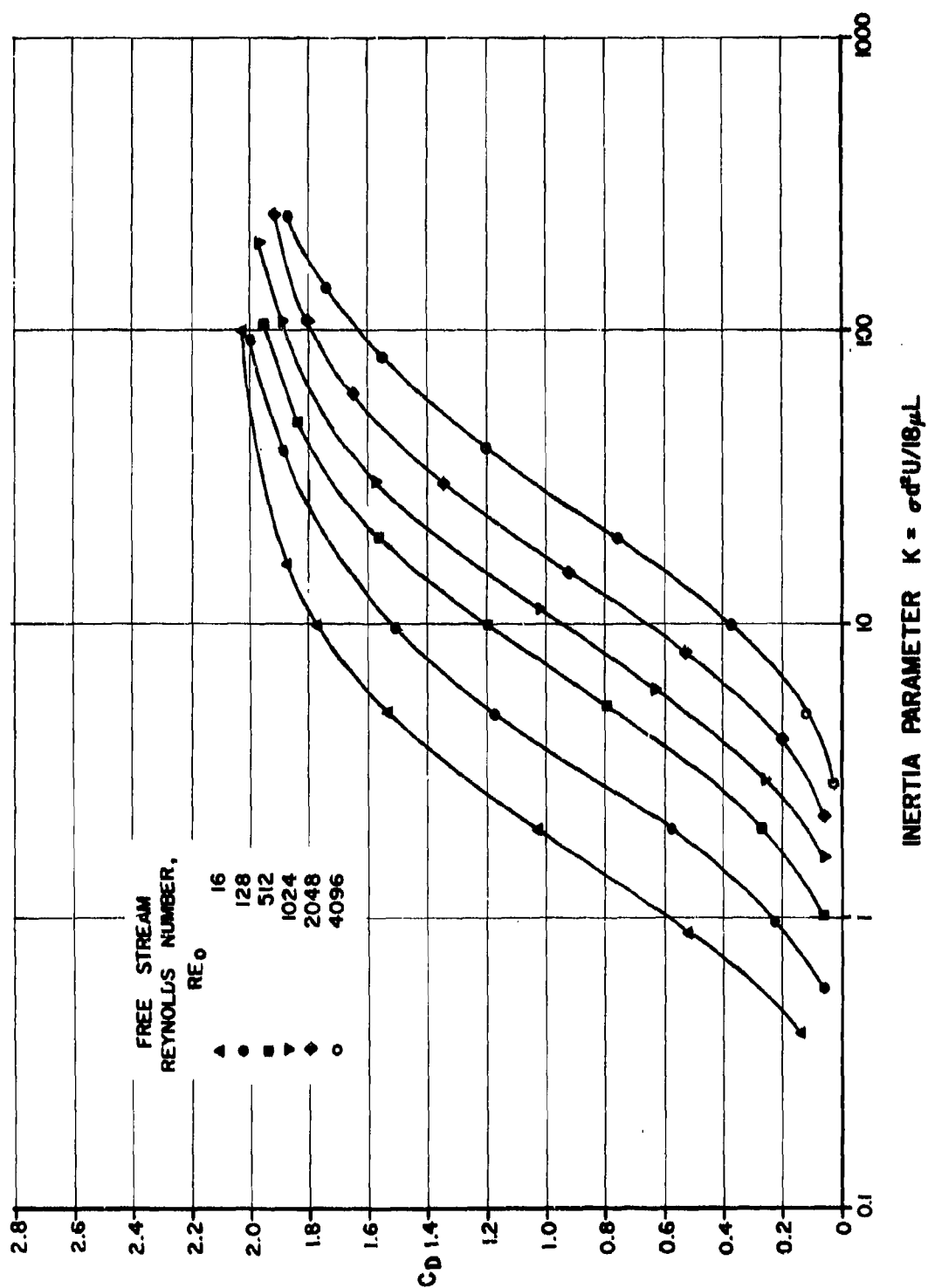


Fig. 8: Impact Efficiency for Spheres for Free Stream Particle Reynolds Number of 128.

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INERTIA PARAMETER $K = \sigma d^2 U / 18 \mu L$

Fig. 9: Calculated Drag Coefficient for Spheres due to Particles alone in an Inviscid Flow.

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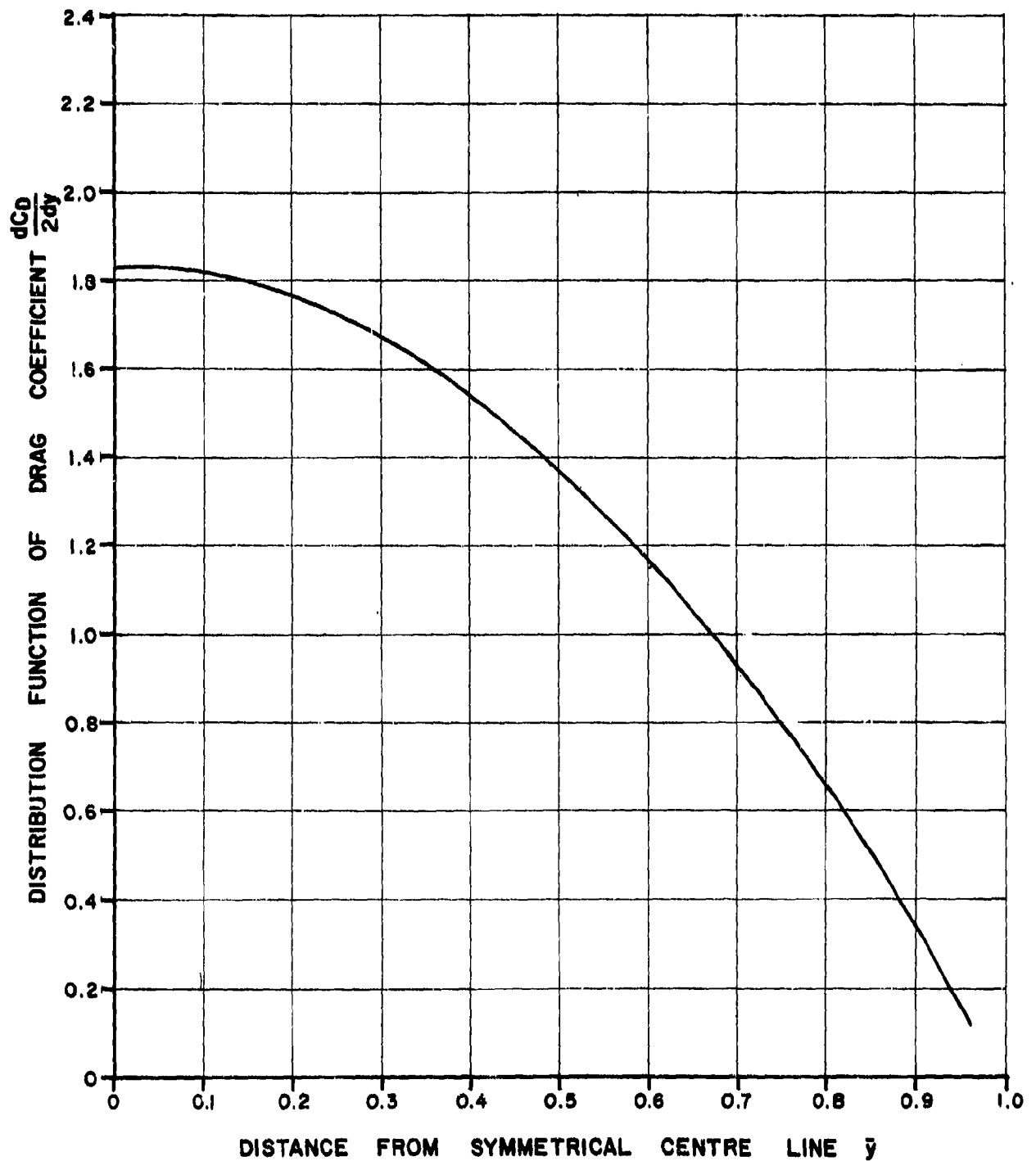


Fig. 10: Distribution of Forces due to Elastic Reflection of Particles from a Cylinder.

$Re_0 = 73.6$ and $K = 339$

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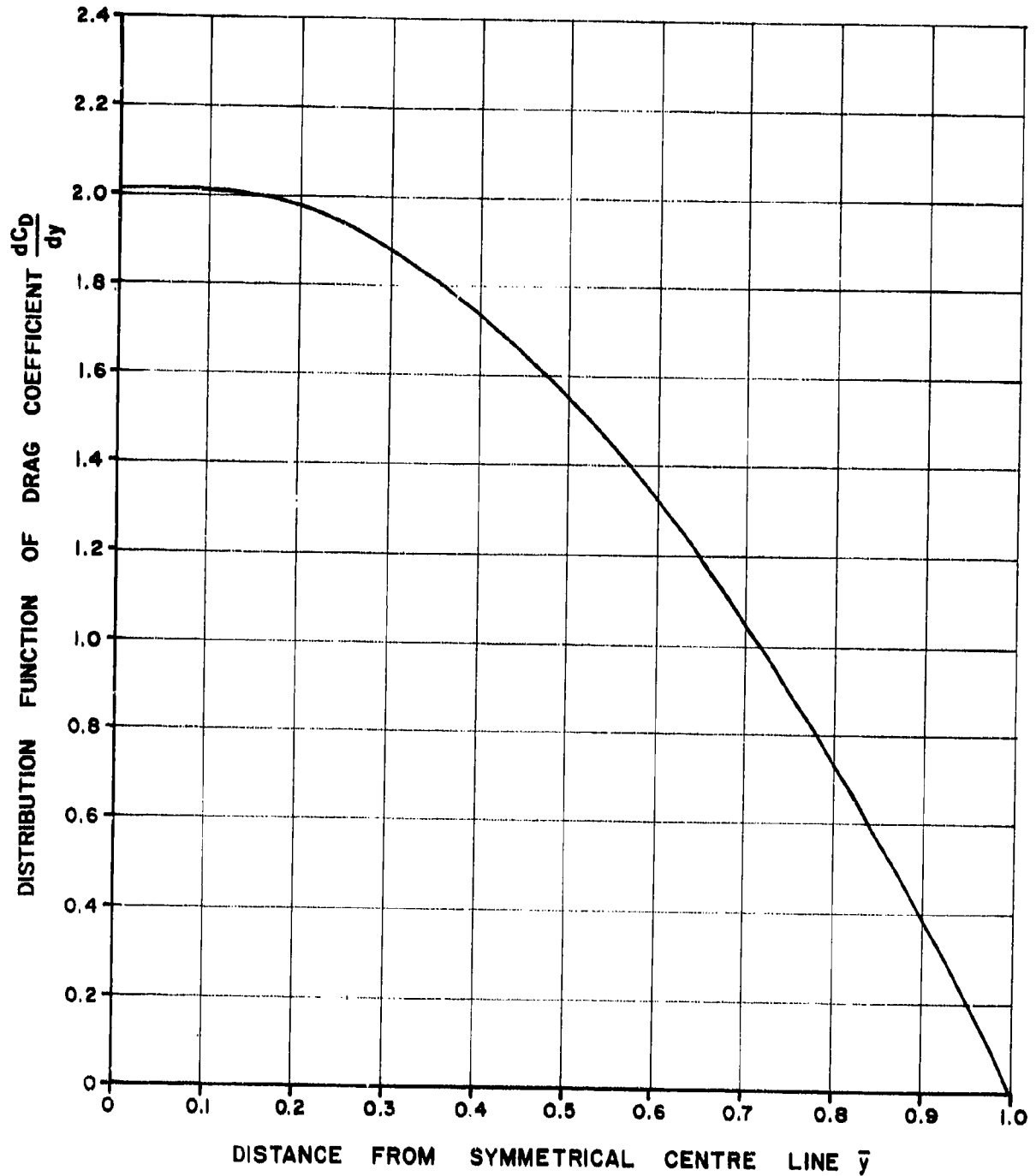


Fig. 11: Distribution of Forces due to Elastic Reflection of Particles from a Sphere in a Tube.

$Re_0 = 73.6$, $K = 339$ and $L = 0.3150$ a

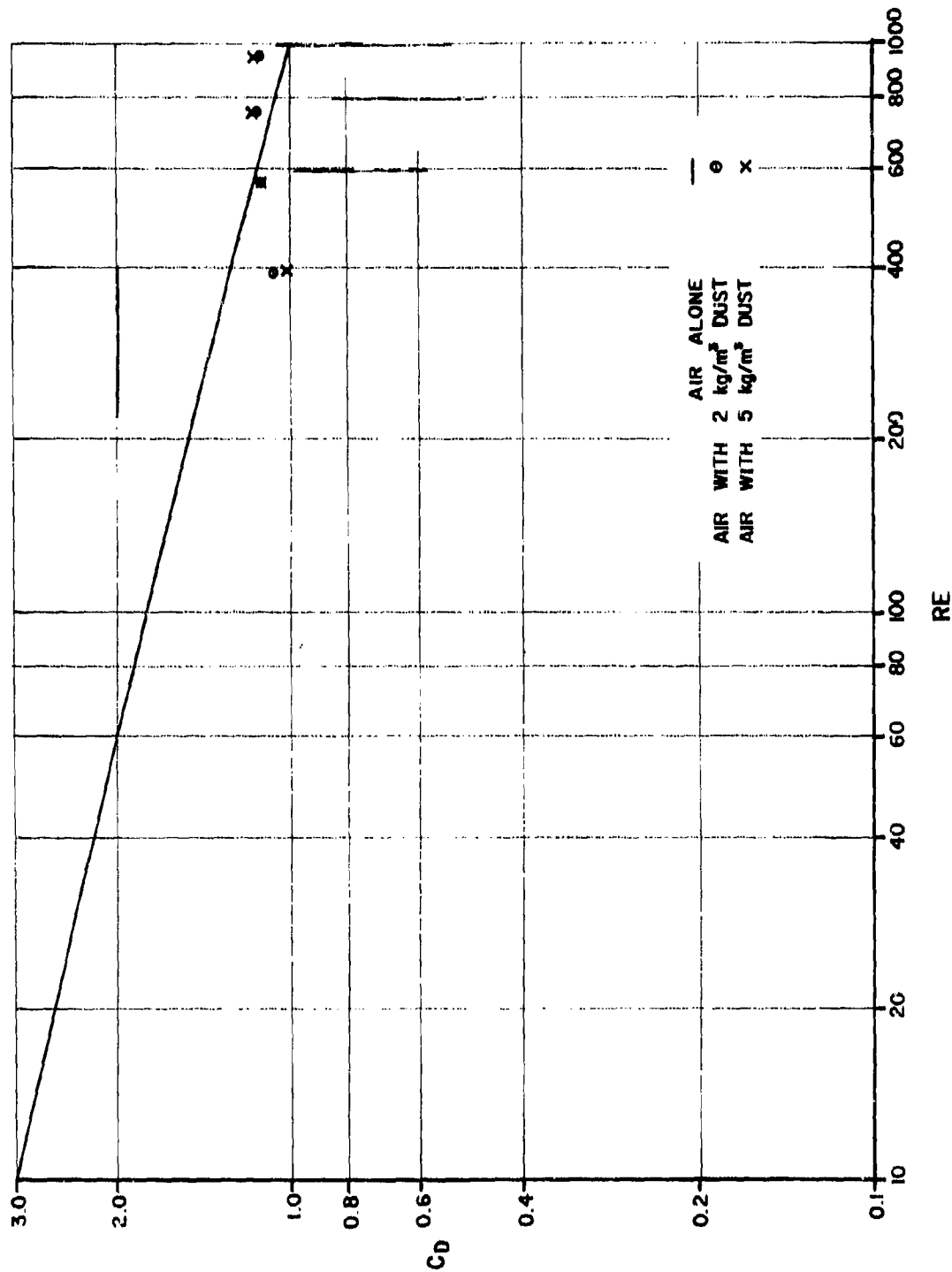


Fig. 12: Drag Coefficient of a 0.2 cm Cylinder in a 2.54 cm Tube due to Equal Masses of 0.0470, 0.0155 and 0.0055 cm Particles corrected for Particle Velocity Deficiency.

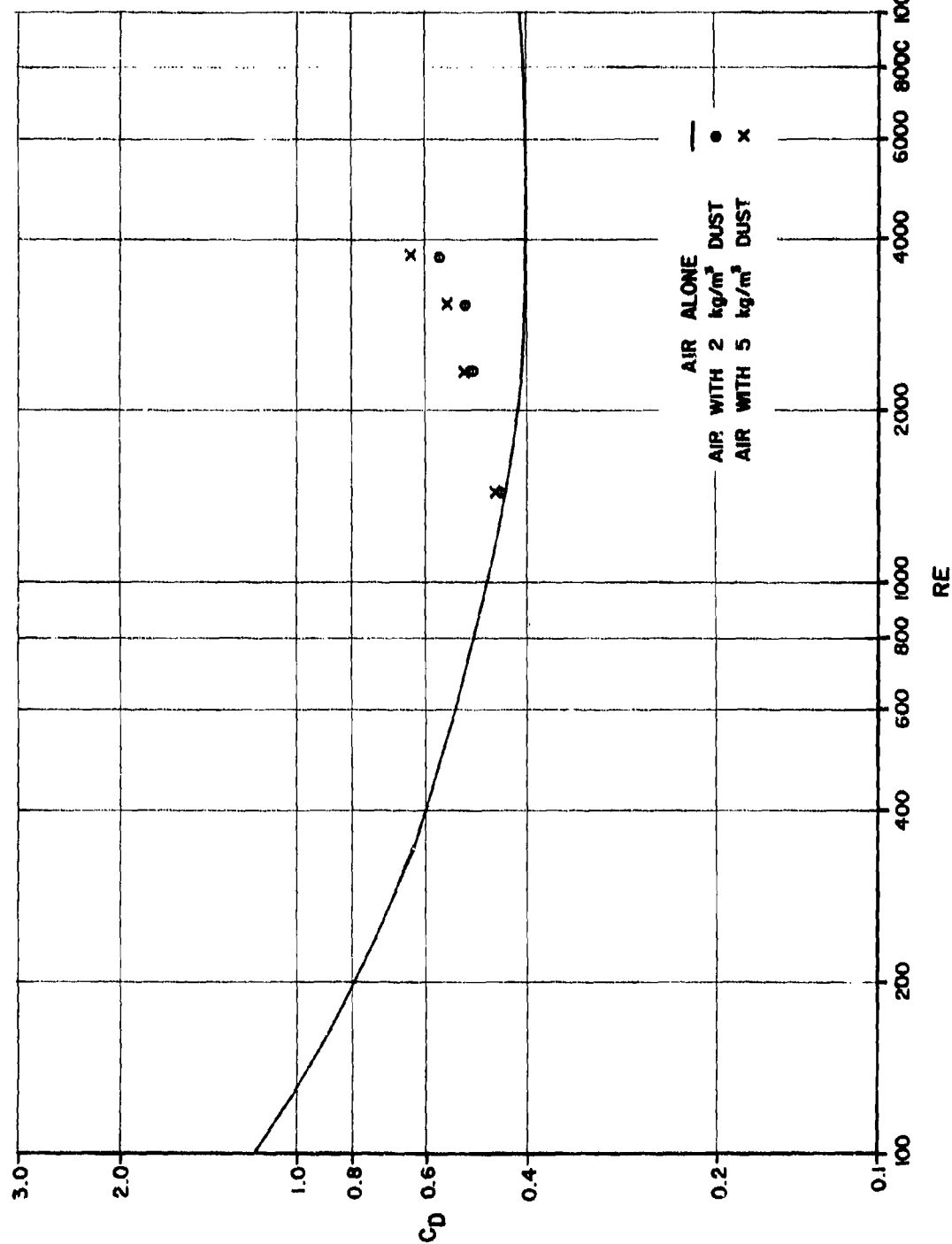


Fig. 13: Drag Coefficient of a 0.8 cm Sphere in a 2.54 cm Tube due to Equal Masses of 0.0470, 0.0155 and 0.0055 cm Particles corrected for real Fluid Velocity and Particle Velocity Deficiency.

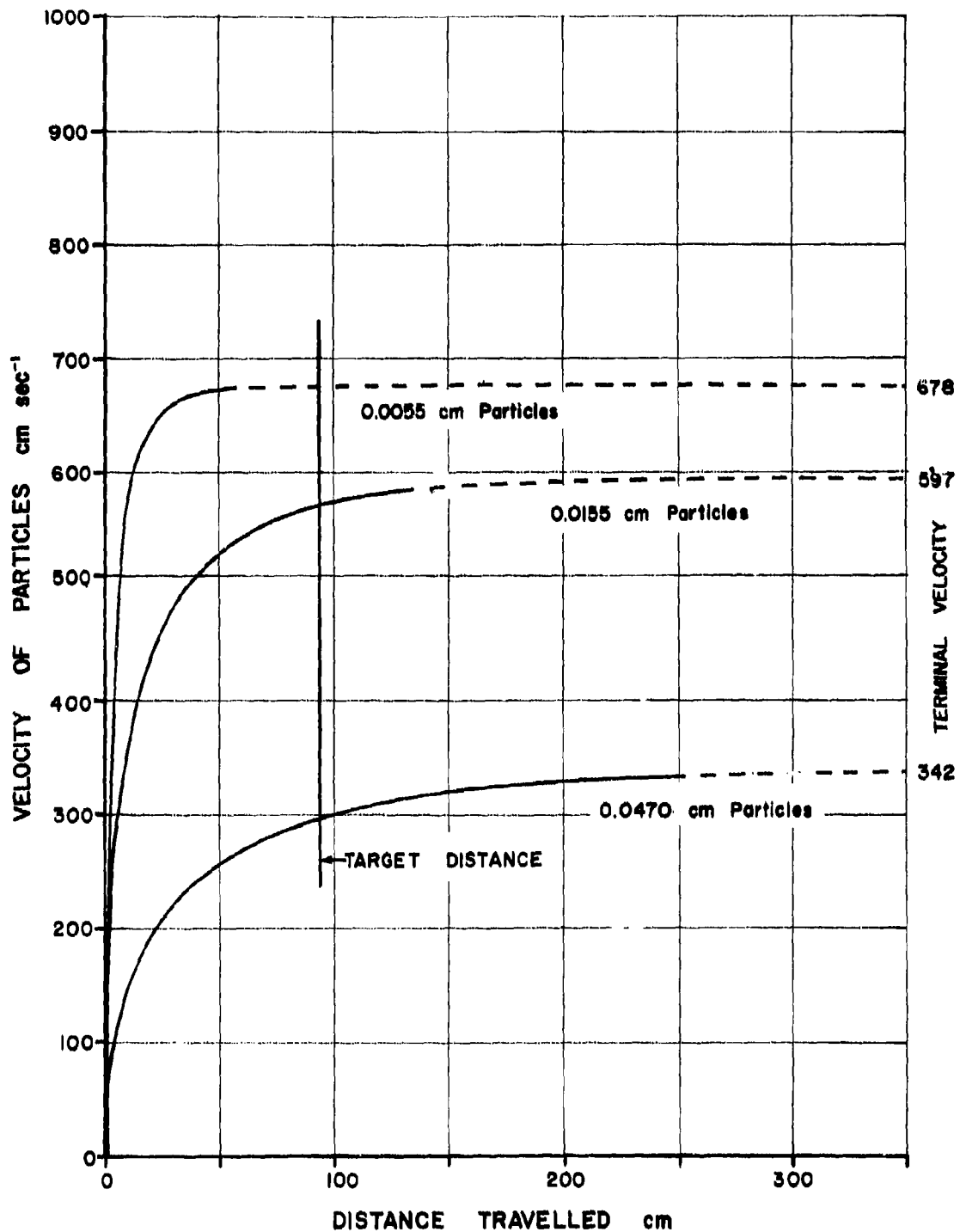


Fig. 14: Upward Velocity of Spherical Dust Particles accelerated from rest in a vertical Air Stream of 700 cm sec⁻¹ Velocity

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		2b. GROUP
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4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Technical Paper		
5. AUTHOR(S) (Last name, first name, middle initial) Mellisen, Stanley B.		
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13. ABSTRACT The effect of dust on aerodynamic drag of spheres and cylinders was calculated by using a mathematical model developed for this purpose. The results were compared to experiments previously done by other workers. The calculated and experimental results agree favourably, showing that the mathematical model is satisfactory. Impaction efficiencies and drag coefficients due to dust alone were then obtained using the model for a wide range of the inertia parameter and the results are presented graphically. The model can also be used for calculating velocity distributions and points of impact for a stream of airborne particles flowing over a sphere or cylinder. (U)		

KEY WORDS

Aerodynamic Drag
Cylindrical Bodies
Spheres
Blast Loads
Dust Particles
Drops (Liquid)
Impact
Aerosols - Penetration
Aerosols - Sampling

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